

Title of Document:

***THE EFFECT OF STAIR WIDTH ON
OCCUPANT SPEED AND FLOW OF HIGH
RISE BUILDINGS.***

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This research investigates the influence of stairwell width on velocity and specific flow of occupants descending stairs during building evacuations. It examines data collected by the National Institute of Standards and Technology taken from eight different stairwells during unannounced fire drills in four buildings. Based on the raw data given by NIST the velocity, density, and specific flow were calculated for each occupant on every floor in which data was collected. Though data was noisy, results demonstrate that there is a linear trend between density of occupants in a stairwell and the velocity they descend at. There is also a parabolic trend between density and specific flow rate of occupants on stairs. While no direct correlation was found, stairwell width does seem to influence the speed and specific flow of occupants since the stairwell with the smallest effective width found occupants traveling slower. As well, the correlations in the SFPE Handbook, developed by Nelson and Mowrer concerning velocity and specific flow rate, were found to be an upper limit on the data that was analyzed.

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RISE BUILDINGS.

By

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Chapter 1: Introduction

This study has been motivated by a need to better understand evacuation by stairways to provide input to code committees responsible for NFPA 101, The Life Safety Code [1] and the International Building Code [2]. In addition, the study is also being conducted to provide fundamental data for performance based calculations of building evacuations and could also be influential to current engineering calculations of people movement. This fundamental data would also be useful for simulation tools that model building fire evacuations.

Current U.S. model codes recognize a linear relationship between stair capacity and stair width, i.e. increasing the stair capacity by one person for every additional 7.6 mm. There are also concerns in that the minimum specified by the Life Safety Code for a building serving over 2000 people is 1.42 m but 1.12 m for a building serving under that amount of people [1]. Some of these minimums are still lower than the minimums specified by researchers such as Fruins and Pauls who studied many building evacuations in the 1970s [3].

Much of the information that exists today on people movement on stairs is data that was analyzed in the 1970s. One of the questions that arises is whether this data is still applicable to the population today, given the demographics that the population is older as well as more obese. It has also been a question as to whether this data that was gathered from observations of buildings up to around 30 stories high can be applied to much taller buildings that are currently being built today. The research described in this thesis will hopefully allow the evacuation community to gain insight into whether the current population of the U.S. behaves as people did

thirty years ago. The current engineering calculations in the SFPE Handbook developed by Nelson and Mowrer for both velocity and specific flow of people on stairwells are meant to be conservative and the data analyzed throughout this research will be compared to these engineering equations.

Chapter 2: Background Information

This section will examine the current research that exists regarding the movement of people on stairs. The review will include previous studies conducted examining stair width, the concept of body ellipses as well as velocity, flow, and density.

2.1 Stairwell Width

Prior to the 1988 edition of the Life Safety Code, a step function was used to address the relationship between clear width of stairwells and flow down stairs. This approach used a lane model for evacuation flow, rather than the linear relationship in the current codes. The earlier codes, mainly the National Building Code in 1905 and the NFPA Building Exits Code in 1913, specified a minimum width for stairways to be 1.12 m, which accounted for two 0.56 m lanes of people that would flow down the stairs at the same time [3]. Both the United States in 1935 and Britain in 1952 published reports that examined the building codes and commented on the lack of empirical data for the lane model. Despite these reports, the 1963 edition of the NFPA Building Exits Code published data about the lane model and the dimensions that would result in an increased stairwell flow. It stated that “a 44-in (1.12 m) stairway comfortably accommodates two files of people; adding 4 in. (0.1 m) to make a 4ft (1.22 m) stairway does not increase the capacity of the stairway. However, it has been shown by count of stairway flows that adding 12 in.(0.3 m) to a 44-in. (1.12 m) stairway does increase the flow of people, in effect permitting an intermediate staggered file” [3]. Although it provided information to say the width needed to increase the flow of people down stairs, this edition in 1963 also did not provide any

scientific references to a study that would validate these assumptions. The lack of empirical evidence for stairwell widths in these early building codes then prompted researchers to study building evacuations.

Jake Pauls studied evacuations from high rise buildings as well as general crowd movement in the 1970s [4,5,6]. He concluded that there was a linear relationship between flow capacity of a stairwell and the effective width of the stairwell and thus developed what is known as the “effective-width model” for stairwells. Effective width is smaller than the clear width in a stairwell as it takes into account the distance that occupants leave in between themselves and the handrail or wall when using a stairwell [4]. This distance or space that is left between the occupant and the wall also takes into account the lateral sway of the occupants as they descend the stairs. Effective width is defined in stairwells as the clear width of the stair minus the boundary layer. For stairwells, the boundary layer is described as 0.15 m on each side of the stair or a total of 0.30 m [4]. When handrails are present in a stairwell, the boundary layer used to measure effective width is 0.09 m from the center of the handrail on each side or 0.18 m for both sides. Handrails are only considered if the effective width of the stairwell using the 0.18 m boundary layer is less than the effective width of the stairwell using the 0.30 m boundary layer, which occurs if the handrails protrude more than 0.06 m into the stairwell [4]. A diagram of how to measure the effective width in a stairwell can be observed in Figure 2-1.

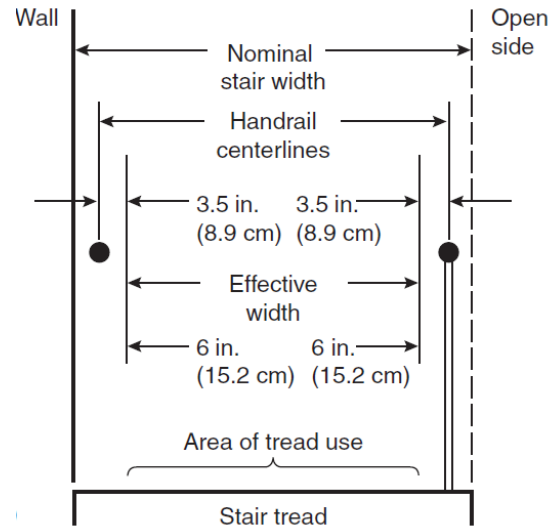


Figure 2-1: Effective width measured in a stairwell [4]

Pauls formulated this “effective-width model” after observation of evacuation drills from 58 different stairwells in the 1970s [5] [6]. Many of these buildings were high rise office buildings that ranged in height from eight to twenty-nine stories [5]. The stairwells he examined also varied extensively in width ranging from 0.914 m to 2.24m [3]. Many of the occupants of the buildings which he analyzed consisted of Canadian government employees [5].

Pauls conducted a statistical regression analysis where he found that the flow was linearly proportional to the measured effective stair width. He performed multiple iterations, compared numerous variables, and then used graphs to check the influence of these variables on the flow of occupants. Once he adjusted his results and removed data such as various stair design or occupancy conditions, Pauls produced a linear regression line that intercepted the x-axis at 0.3 m (12 inches) [6]. This was the basis of his correlation presented by equation 1 below, in that the mean flow of people descending stairs is proportional to the stair’s effective width or the wall to wall width minus 0.3 m. This statistical analysis was also supported by video

records from three different stair widths in which despite densely crowded stairs, nobody occupied .15 m on either side of the stairwell [6]. This result can be observed in a diagram produced by Dr. James Milke to depict this situation in Figure 2-2 below

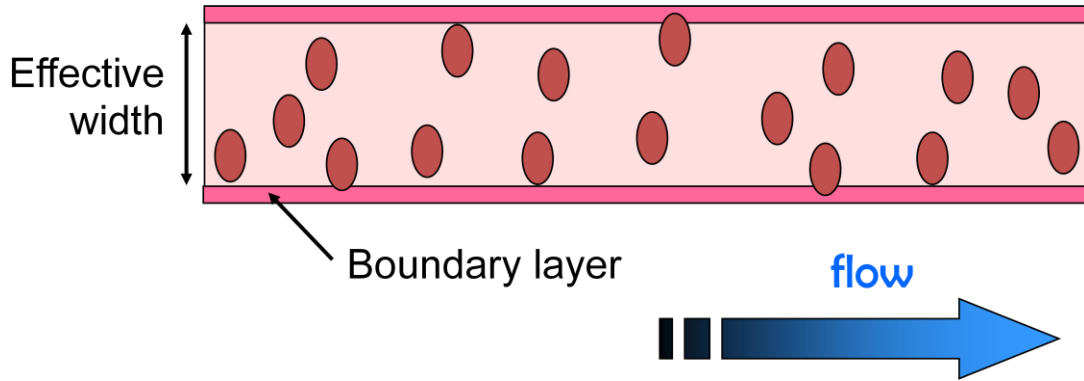


Figure 2-2: Diagram of Occupants Not Using the 0.15 m Close to the Wall (Boundary Layer)

Pauls' findings indicated that for every incremental increase in stair width, a corresponding increase in the flow rate was observed. He developed an equation to calculate the mean flow per person per second expected on a stair given the evacuation population and the width of the stairs. That correlation is

$$F = .206(w - .3) \left[\frac{P}{(w - .3)} \right] (0.27) \quad (1)$$

where P is the evacuation population and w is the actual stair width measured. Using this equation, Pauls also developed a model to determine the width of a stairwell given a desired overall evacuation time

$$W = \frac{8696 P}{T^{1.37}} + 300N \quad (2)$$

where P is the number of people flowing through the stairwell, T is the flow time, W is the total width of the stairs in mm and N is the actual width of the stairs. As the desired overall evacuation time, T does not include the pre-evacuation time, the time

is a minimum time which means this stair width determined from the equation should be a minimum width. Based on his research, Pauls recommended a minimum width of stairwells to be 1.4 m, which would allow for occupants to travel in two lanes and would also account for body sway. This size stairwell would also allow an occupant traveling in the middle of the stairwell to be able to access the handrails on either side of the stair [6]. However, Pauls has also pointed out more recently that this minimum width relationship may not be accurate today since the relationship is based on observations that were made decades ago and user demographics have changed significantly over this time period [3].

Fruin also studied people movement on stairs in the 1970s. He used both observation and photographic evidence to examine movement on stairs and developed the following correlation for flow based on his analysis [7]:

$$P = \frac{128M - 206}{M^2} \quad (3)$$

where P is the volume of pedestrians per minute per foot of stairway and M is the square foot area per pedestrian. Fruin, like Pauls recommended a minimum width for stairs. He recommended a slight larger minimum width than Pauls of 1.52 m [3]. Like Pauls, Fruins' estimate also accounted for two lanes of people with 0.56 m shoulder width, however Fruin added 0.1 m per person on each side to account for lateral body sway, while Pauls' recommendation was based on a 0.1 m lateral body sway by each person towards the outside of the stairwell and 0.1 m in between the two lanes [3].

Templer, Mullet, and Archea conducted an analysis of fifty hours worth of video recording of people using stairs. These videos were taken from different parts

of the United States and observed a variety of stair users ranging from pre-school children at two day-cares to elderly people at community centers to young adults at a university student center to a large sampling of individuals at two shopping centers [8]. The stairs that were taped were located both inside as well as outside of buildings and had different designs with different dimensions for risers, treads, and widths as well as different configurations which can be observed below in Figure 2-3 [8].


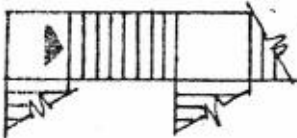
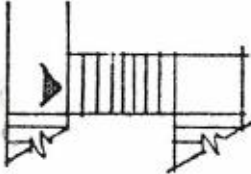
PLAN	RISER	TREAD	WIDTH
	6	11	60
	6	11	60
	6	11	59

Figure 2-3: Variations of Stairs Observed by Templer, Mullet, and Archea [8]

Their ultimate goal in analyzing the videos was to make performance statements for optimal stair design to avoid accidents. Since the hazardous nature of stairs was being examined, Templer et al. recommended that stairs be wide enough so that traffic can move at a comfortable speed and thus individuals will not be congested and their speed slowed, which would make it harder for them to balance as they shifted back and forth from stair to stair when they traveled slower. Thus, they recommend that stairs be wide enough so that individuals do not assume an awkward gait in order to travel side-by-side down the stairs. For two-way stair traffic, they recommended that stairs have a minimum width of 1.4 m between walls and 1.75 m for comfort [8]. For ease of use and to avoid stair incidents, Templer et al. also recommend that the riser and tread height should be based on their data which matched riser height to tread width. However to avoid incidents, risers should be between 0.16 and 0.18 m and treads should be big enough (not less than 0.28 m) to accommodate the average person's foot [8]. They pointed out that handrails should be on both sides if there was two-way traffic and should be of materials that were smooth [8].

The work of these researchers concerning stairwell widths influenced the Life Safety Code to expand its minimum stairwell width for a building serving over 2000 people from 1.12 m to 1.42 m. However, for a building serving less than 2000 people, the minimum width is still 1.12 m which is smaller than the minimums recommended by both Fruin and Pauls of 1.52 m and 1.4 m respectively [3]. Though their work was influential, the analysis concerning lateral body sway on stairs pertains to observations and demographics of individuals from three decades ago.

2.2 Study of Body Ellipses in People Movement

Early models of pedestrian movement as well as design specifications for recommended stair width made use of the concept of an ellipse to represent an individual during evacuation. Both Fruin and Templer conducted analysis of the human body and ellipse but they both based it on work conducted by Albert Damon [7] [9]. Damon from Harvard, compiled dimensions of people from numerous human factors studies based on the shoulder breadth and body depth of a person. Damon indicated that the shoulder breadth of civilians was 0.51 m and soldiers was 0.55 m [7] [9]. One of the reports Damon analyzed was a study of laborers based on the view from above which stated that the upper percentile could be categorized into an ellipse that was 0.55 m wide by 0.30 m in depth [7]. Fruin also reported that he thought an ellipse of dimensions 0.61 m by 0.46 m was a more realistic dimension based on the desire of humans to avoid close interactions and that the majority of them are carrying something [7]. This ellipse of 0.61 m by 0.46 m was also used in the late 1960s by the Army for human body dimensions in the design of communication systems and was used to develop the design capacity for subway cars in New York City [7].

Templer also examined the space needed by occupants on stairs based on the dimensions of the human frame at rest as well as during movement based on previous research studies. Templer also identified the shape of the human body when viewed above from rest resembled that of an ellipse [9]. Templer reported that Time Saver Standards, interior design and space planning book of standards from 1966, recommended for the minimum width of a single-file stair (no handrails) to be 0.61 m for “comfortable human passage” and suggested 0.76 m as a better width of stairs [9].

A study by Saunders in 1953 added that 0.04 m should be added to either side of a person based on the lateral sway when an individual is descending stairs as the occupant shifts their weight back and forth upon moving down stairs [9].

Fruin's research based on photographic evidence stated that when the population on stairs became denser, and the gait of a person was reduced to a shuffle, the sway was more pronounced and 0.1 m should be added to either side of a person [9]. Templer added another 0.05 m (0.025 m on each side) to each ellipse to account for clearance between the person's clothing and the stair wall. Using these numbers, Templer reasoned that it would be comfortable for an occupant travelling in a single file if the stair had a minimum width of 0.97 m between walls. For a staircase where people would walk side by side the width should be a minimum of 1.4 m between walls but 1.8 m was recommended [9].

Like Fruin, Templer expanded on the concept of using the ellipse to represent the dimensions of an occupant to examine how the ellipse might change during motion or an evacuation. Templer determined that on most stairs, an individual most likely occupied two stair treads, having one foot on the tread behind them and one foot on the tread in front of them. Based on those assumptions, Templer concluded that the pacing zone for an individual moving on stairs would be the area of two treads, and thus the dimensions based on a 0.28 m tread was 0.51 m² or 0.56 m in depth and .91 m in width, as indicated in Figure 2-4 below [9].

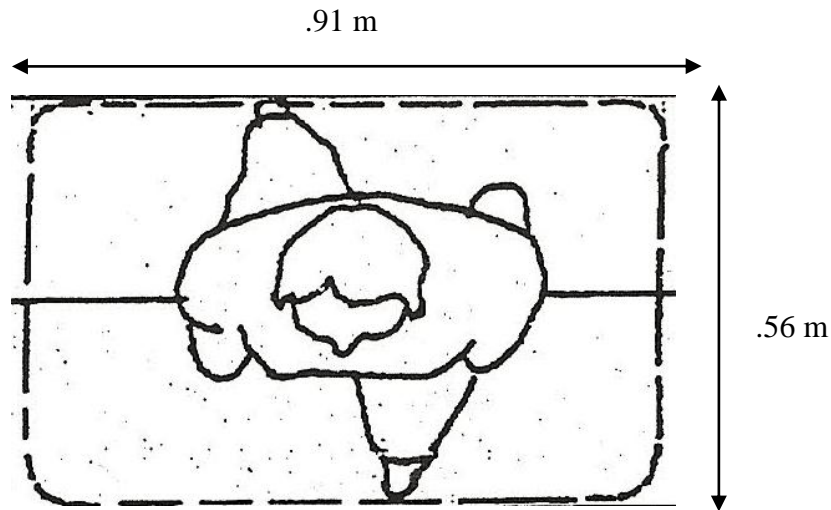


Figure 2-4: Templer Diagram of Movement on Stairs [9]

Fruin also identified what he referred to as the “sensory zone” which he considered a bubble of space that individuals keep between themselves and their environment i.e. objects or people surrounding them [7]. On stairs however, the sensory zone is smaller as the pacing length, or length needed for movement is structured by the treads on the stairs. Fruin found through analysis of pedestrian traffic flow descending stairways that as the density was increased to where the usable area was reduced to 1.39 m^2 people will begin to slow [7] [9]. At a density of approximately 0.139 m^2 per person, people stopped throughout the stairwell, and movement became almost impossible, as this meant that each occupant would occupy about one tread [7] [9].

Pauls examined the effect of density on evacuation dynamics and models. Fruin’s early model of evacuation had the plan view of people represented by ellipses. Pauls concluded that this concept of ellipses was accurate when there were high-

density and low-speed conditions. However, when the density of the occupants was small, the body was a different shape than the ellipse when viewed from above. Pauls found that when there was a low occupant density, a circle was a better approximation than an ellipse because the legs of the individual were to the front and back, thereby creating a circle rather than the ellipse proposed by Fruin where the legs appear to be directly underneath the shoulders [10]. This is indicated in Figure 2-5 shown below [10]:

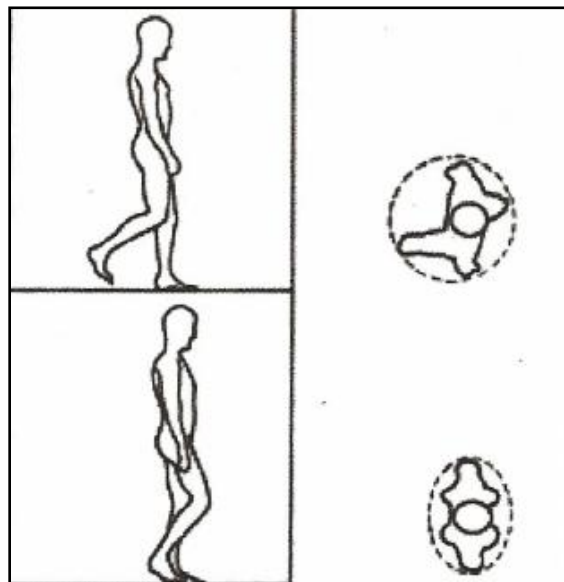


Figure 2-5: Pauls analysis of the plan view of an occupant [10]

2.3 Speed, Density, Flow

Predtechenskii and Milinskii conducted observations of people movement that led to correlations about the speed of occupants descending stairs. These observations were based on an actual observer who chose one person in a given area and monitored the time between when the person entered and exited this area all while counting the number of people that passed the observer. They then stopped

counting when the person chosen at random had reached the observer. These observations were then repeated multiple times as occupants descended the stairs. From these they were able to develop correlations in which they found that the velocity of people descending stairs was directly related to the density or number of people that surrounded them. Predtechenskii and Milinskii's correlations based density on the number of people per the area they occupied but also upon the season, age of the individual, and whether or not they were carrying a bag. They determined that as density increased on the stairs, the speed of the occupants decreased [11].

An actual study of density versus speed and stairwell width during building evacuation was conducted in Japan in the mid 1980s. Kagawa et al. in Japan examined a high rise fire drill evacuation of a 53 story building in Japan in 1984. It was estimated that about 1500 people took part in the drill and were observed through video cameras which were placed on the inside and outside of the stairwell on three floors as well as staff that held video cameras and participated in the evacuation. In their study, four observers egressed with the building occupants. The findings of this fire evacuation on the 1.2 m stairwell (minimum in Japan) were that only one evacuee occupied each step of the stair and occupants were usually staggered on the stairwell, either alternating between the left and the right side of the stairs or there were two on one stair but the next person was two steps away. This resulted in a density of 1 person per stair or about $0.33 \text{ m}^2/\text{person}$. A higher density was rarely observed even during times where the velocities of the occupants were very slow [12].

The average speed observed during evacuation was 16 seconds per floor (3.65 m) without disturbances, which reflected an expected value for individuals moving

down stairs unobstructed [12]. Due to congestion, it took some occupants around 20 seconds to travel one floor. There were observed instances of people on higher floors waiting for occupants on lower floors to enter the stairs which caused stagnation. Also, from the observed density it seemed that each stairwell could only hold approximately 40 people per floor instead of the 200 which evacuated. They concluded if multiple floors evacuate at the same time a standstill will occur and thus the stair width was insufficient [12].

In the SFPE Handbook, Nelson and Mowrer [4] developed correlations using data by Pauls, Fruin, and Predtechenskii and Milinskii. These correlations are based around the idea that evacuation flow speed of a group is a direct result of population density. Nelson and Mowrer said that for densities less than 0.54 persons/m², people will move at their own speed and it will not be affected by the speed of others. At a density greater than 3.8 persons/m², they said that no movement would take place as it would be too crowded for individuals to move [4]. This upper limit was based on a regression analysis of speed versus density, though no measurements had been obtained to confirm this upper limit. A critical density between these two limits (0.54 persons/m² and 3.8 persons/m²) was then defined to have a linear relationship given by [4]:

$$S = k - akD \quad (4)$$

where S is the speed (m/s) along the line of travel, D is the density (persons/m²), a is a constant of 0.266 when the speed and density are in metric units, and k is a constant based upon the stair riser and tread dimensions as observed in Table 2-1 below [4]

Stair Riser (in)	Stair Riser (m)	Tread (in)	Tread (m)	<i>k</i> for metric units
7.5	0.19	10	0.25	1
7.0	0.18	11	0.28	1.08
6.5	0.17	12	0.3	1.16
6.5	0.17	13	0.33	1.23

Table 2-1: Constant *k* for SFPE speed correlation [4]

Based on equation 4, a correlation was then developed for the specific flow, which is the flow of a person moving past a certain point in the exit route per unit time, per unit of effective width. Nelson and Mowrer's correlation is given as [4]:

$$F_s = SD \quad (5)$$

where F_s is the specific flow in persons/s/m_{effective width}, S is the speed of movement (m/s) calculated using equation 4, and D is the density (persons/m²).

All of these correlations in the SFPE Handbook are based on previous correlations and by data that was collected mostly in the 1970s. Also, as Pauls pointed out at the Human Behavior Symposium in 2004, there is limited information concerning evacuation behavior within stairways of high rise buildings [10]. Most of the data that exists is based on Pauls' research in Canada over three decades ago. His research mainly focused on buildings no higher than 27 floors and the findings are applied to buildings up to three times the size. Further, his conduct of the evacuation drills was done where the occupant speed down stairs was artificially reduced by members of the research team leading the participants, so that natural flow conditions were not observed in the stairways [10].

Pauls also discussed the implications of using data from different cultures such as from Canada (Pauls), United States (Fruin), Predtechinskii and Milinksii

(Russia), Japan (Kagawa, Togawa) [10]. All in all, there is evidence from these researchers that there are strong correlations between density, speed, flow, and effective width of stairs. However, the majority of it is from three decades ago and doesn't consider the changes in demographics such as the obesity epidemic in the United States.

2.4 Background Information Summary

Based on his research in the 1970s, Pauls developed the “effective-width model” where he developed a correlation between the flow of individuals down stairs and the effective width of a stairwell [5] [6]. Multiple researchers also studied the lane model approach of people on stairs to recommend minimum widths of 1.4m-1.75 m, 1.52 m, and 1.4 m by Templer et al, Fruin, and Pauls respectively [3] [8]. This research while important has not been taken into account in the current building codes which give a minimum stairwell width for a building serving over 2000 people to be 1.12 m to 1.42 m. However, for a building serving less than 2000 people, the minimum is still 1.12 m [1] [2]. The shape and how people moved on stairs was researched by Pauls, Templer, and Fruin who saw individuals sway on stairwells as they shift their body gait and avoid coming close to others as well as the walls [7] [9] [10]. Researchers in Japan examined evacuations that led to the idea that people are typically staggered on stairs and do not exactly follow the lane model [12]. Many of these ideas and correlations led to the correlations developed in the SFPE Handbook from Nelson and Mowrer in which specific flow is linearly proportional to density and speed of a person descending a stairwell [4]. Much of the research that has been

studied in this area is all based on demographics and data from the 1970s and 1980s which may not be relevant to today's society.

It is evident from the recent Pedestrian Evacuation Dynamics (PED) conference held at NIST in March of 2010, that there still remain many questions concerning the movement of people. These questions have arisen due to an increase in the age of the population throughout many countries as well as an increase in the rate of obesity who all present challenges to the evacuation process during emergency situations. Many different individuals are currently studying issues throughout the world such as evacuation data collection, modeling of people movement and validation of these models.

The research described in this thesis will hopefully allow the evacuation community to gain insight into whether the current population of the U.S. behaves as people did thirty years ago and also gather quantitative data for high density evacuations with varying stair width to determine whether the current model code requirements accurately portray the evacuation needs of the occupants to safely and timely egress the building.

Chapter 3: Building Evacuation Data

3.1 Building Descriptions

The data examined and analyzed for this research pertained to unannounced high-rise office building evacuations that were observed by the National Institute of Standards and Technology (NIST). This data was collected by video cameras located throughout the stairwells during fire drill evacuations of these buildings. These cameras were placed on every other floor and captured the floor's main landing, the doorway into the landing, and two to three steps on either side of the landing [17]. Using the data collected by each camera, NIST was able to measure the time each occupant exited the stairwell, the time each person passed a camera in the stairwell, and the floor of entry for each individual [14].

As of April of 2009 when they presented at the annual NIST fire conference, Peacock, et al. had collected data from fire evacuation drills of eight high-rise office buildings [14]. In each of the buildings, there were typically between 600 and 1200 occupants that participated in each evacuation drill, and between 200 and 500 occupants observed in each stairwell [13][17]. Since this research examines speed and flow with respect to the width of stairwells, only the evacuations in buildings that had stairwells that experienced high densities of people during egress were considered as these are the only cases when stairwell width is expected to be important. If buildings with low density were considered, occupants would be free to walk at the pace they desired and the width of the stairwell most likely would not impact either their speed or flow down the stairwell. Since the stairwells were selected for analysis prior to a quantitative evaluation of density, high density in a

stairwell was qualitatively defined by whether or not there was slowing down or stopping by occupants throughout the stairwell during evacuation.

Of the eight buildings from which data was collected by NIST there were only four buildings in which density of people on the stairwells was considered to be high [14]. Within these four buildings, NIST collected egress data from a total of ten stairwells. Two of these ten stairwells were from Building 4, a 24 story office building and they were both 1.12 m wide. There was data gathered from two stairwells in Building 5, a ten story office building in which the stairwells were 1.27 m wide. Data was collected from four stairwells from Building 7, an 18 story office building, that were 1.12 m wide. Also, data was collected from two stairwells of 1.37 m width from Building 8, a 31 story office building [14]. While all four buildings experience high densities during egress, they varied in both height as well as stairwell width. A summary of all four buildings being analyzed is presented in Table 3-1.

Building Number	Occupancy	Number of Floors	Stair Width	Number of Stairs Observed	Density of People
4	Office	24	1.12 m	2	high
5	Office	10	1.27 m	2	high
7	Office	18	1.12 m	4	high
8	Office	31	1.37 m	2	high

Table 3-1: Summary of Buildings to be Analyzed

Of the data presented above in Table 3-1, only eight of the ten stairwells that were observed will be analyzed in this study. Building 7 had a stairwell (Stair 12) that experienced counter flow, as firefighters were sent up the stairwell as occupants were descending it. This counter flow could affect the speed and flow of occupants descending the stairs so the data from this stair was not taken into account. Also, the data from the North Stair in Building 8 was not yet fully analyzed and therefore was

not included in the data presented by NIST [17]. A summary of the number of occupants observed and the clear widths as well as the effective widths of the eight stairwells being analyzed is shown in Table 3-2. Though Building 4 and 7 have the same clear width, Building 7 has handrails that protrude into the stairwell more than .06 m [17], so as outlined in Section 2.1, the effective width would be based on the boundary layer from the handrails instead of just the boundary layer from the clear width.

Stairwell	Number of Occupants	Clear Width (m)	Effective Width (m)
4A	249	1.12	0.82
4B	356	1.12	0.82
5A	436	1.27	0.97
5B	368	1.27	0.97
7-1	255	1.12	0.73
7-3	292	1.12	0.73
7-7	340	1.12	0.73
8	538	1.37	1.08

Table Error! Use the Home tab to apply 0 to the text that you want to appear here.-2: Number of Occupants, Clear Width, and Effective Width of all Stairwells Analyzed [17]

3.2 Data Collection

As a previous intern at NIST, Blair helped to extract some of this raw data from the video cameras. The first step in the process was to digitize the video footage. The program Final Cut was used for this process in which the footage from the camcorder was made into a digital video that could be analyzed directly on a computer screen. There was a separate recording for every other floor in all the stairwells in which data was collected. The lowest floor, floor of exit, in the stairwell was the first video to be analyzed using movie inspector, a feature in the program

Quick Time that displayed the time to the nearest hundredth of a second. Once the video was started, the time at which the alarm sounded in the stairwell was the first thing recorded. This step is important because each camera was not started at the exact same time. Consequently, all of the evacuation times can be determined relative to the alarm time on all floors so that the entire building was then using the same start time for evacuation.

The videos were then analyzed by collecting data on each occupant as they descended the stairwell. Each occupant was given a number in the order that they descended the stairwell once the alarm had sounded on the exit floor. For instance, the first occupant to exit the building would be identified as Occupant 1, the second Occupant 2, and this number increased until the last individual was observed exiting the stairwell. After all the occupants were given a number and exit times, they were then tracked and the times were recorded when they entered and exited the stairwell on every other floor above the exit floor. For instance, if an occupant entered the stairwell on floor 9, their entry point could be seen and the times relative to the fire alarm were noted on floors 7, 5, 3, and the exit floor 1. The timeline in which the data was collected can be observed below in Figure 3-1.

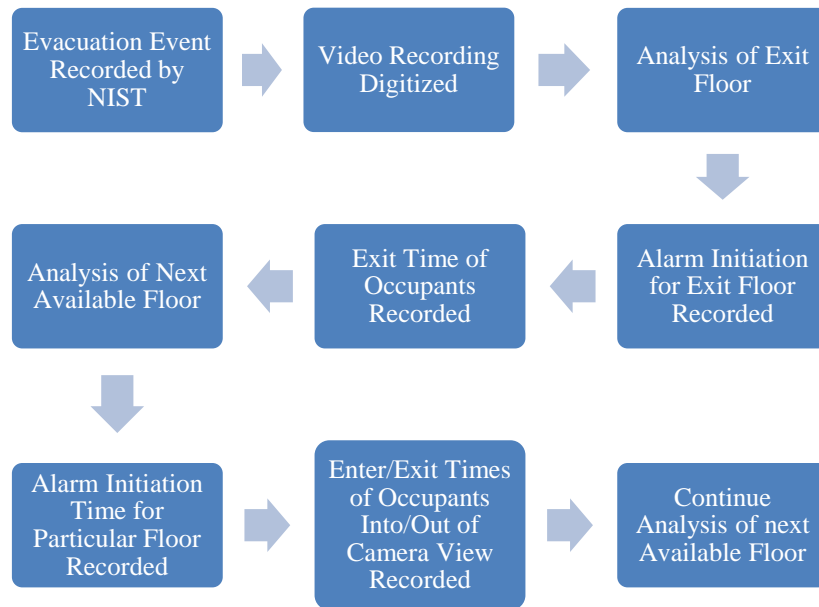


Figure 3-1: Timeline of Evacuation Event Analysis

The enter and exit times for each stairwell were based on the number of stairs that were clearly visible in the camera view. For someone entering the camera view from the floor above their enter time would be when their foot cross the plane shown by the green line displayed in Figure 3-2. If the occupant entered the stairwell on that particular floor, their enter time was recorded as soon as their foot crossed the plane of the yellow line in Figure 3-2 as the occupant stepped off of the landing. The exit point for occupants either entering the camera view from the floor above or the stairwell on that particular floor was the same. This point can be noted as the red line in Figure 3-2 below and is the last step that can be clearly observed in the video frame.



Figure 3-2: Stairwell Identification of Enter/Exit Locations [17]

Not all of the cameras captured the same view of the stairwell as depicted above and it was noted for each floor the location at which that times were determined for each occupant. This is evident from Figure 3-3 below which was taken from Jessica Kratchman's thesis from 2007 [15]. Kratchman also examined evacuation data that NIST collected. This Figure depicts two images of two different camera angles from the same building. One can note that in the image on the left the lower part of the stairwell is more visible than the upper part while this is not the case for the individuals in the image on the right in which the upper part of the stair is easier to observe.



Figure 3-3: Images of Camera Angle Views from the Same Building [15]

3.2 Validity of Using Evacuation Data

The data from all four high-rise buildings were gathered during unannounced evacuation drills. They occurred before lunch time but during regular business hours [17]. The results from these evacuation drills represent a good prediction of an actual fire event based on findings by Proulx who studied how a drill would relate to an actual fire scenario [16]. Individuals in emergency situations have been observed to think logically and act reasonably as opposed to the contrary belief that people panic during fire conditions. In these situations, pre-movement activities have been observed where occupants first hear an initial fire cue and then often take time to gather more information either on their own or from those around them. In an actual fire emergency people “should not be expected to react faster or move more efficiently” [16]. Since this logical thought process has been observed in real fire situations it can be concluded that the movement of people during evacuations drills can be a good predictor of their actions during real emergency conditions. Since the evacuation drills conducted by NIST were unannounced they are a good basis for making conclusions concerning the movement of the occupants and how they would behave if their building had an actual fire. However, it is necessary to note that this data is not real emergency data and therefore while it serves as a potential predictor of a fire or emergency situation, the data analyzed cannot be completely conclusive of an actual fire scenario.

Chapter 4: Data Analysis

The data that was analyzed in this research was collected by NIST and was provided in the form of a spreadsheet [17]. As discussed in Section 3.1, the spreadsheets contain a list of the number of occupants that exited from the stairwells and the enter/exit times for each floor at which they were observed throughout the evacuation drill. If an occupant was observed entering the stairwell on a particular floor it was evident the floor in which they began the evacuation. If they were not observed entering the stairwell they were then assumed to enter the stairwell one story above the floor on which they were first seen by the camera. This assumption is made since the cameras only recorded the evacuation on every other floor so if the individual was not directly observed entering, then it was concluded they entered the stairwell on a floor that did not contain a camera. For example if data is available for an occupant who was in the camera view on floor 3 walking down the stairs towards the 3rd floor landing and there was no time recorded for the occupant on floor 5 (where the next camera was located), then they were assumed to have entered the stairwell on floor 4.

4.1 Occupant Enter and Exit Times

The first objective was to synchronize the data so that all of the times in the spreadsheet were relative to the alarm initiation throughout the building. Since the videos on different floors were started at different times, the times in the spreadsheet corresponding to when an occupant entered and left the camera view on a certain floor was the time starting when that particular camera began recording. In order to convert all times to a common baseline, the times for each occupant were converted

to seconds and the alarm time was then subtracted from this. This would mean that time $t=0$ seconds refers to the alarm activation time. On the exit floor, these times corresponded to the total evacuation time of each individual throughout the building starting from $t=0$.

4.2 Distance and Area Calculations between Camera Views

4.2.1 Distance between Two Flights of Stairs Using Stair Geometry

Along with the time data that was provided for each occupant in the spreadsheets from NIST, each stairwell had a table of distances from camera to camera. These distances were verified using information about the schematics of each stairwell as well as research from Predtechenskii and Milinskii. For example, in Building 4 the stairs have a 0.18 m rise and a 0.28 m tread. Using these values, the distance traveled down each flight of stairs was determined using the Pythagorean theorem. This distance diagonally of one step was calculated to be 0.33 m and is shown in Figure 4-1.

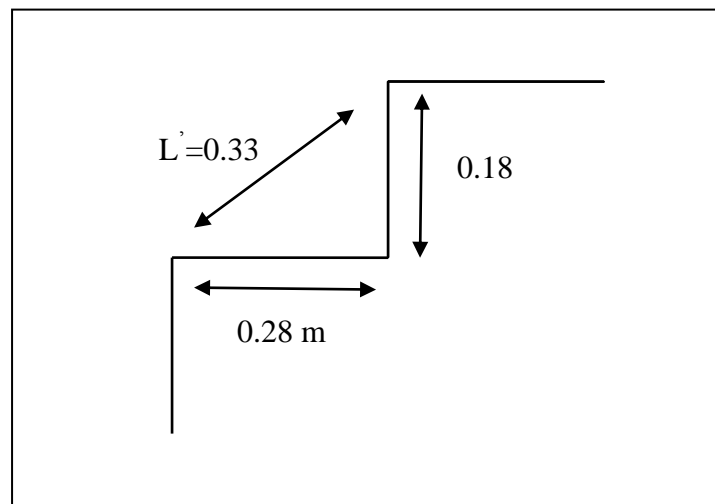


Figure 4-1: Diagram of Stair Dimensions from Building 4

The length traveled was calculated for a particular flight of stairs by multiplying the value calculated above by the number of steps in each flight. In Building 4, floors 24 to 3 have twenty steps between floors with ten on either side of the mid-landing. This means that the distance traveled for one staircase would be $0.33\text{m} \times 10 \text{ steps} = 3.3 \text{ m}$.

The distance traveled between floors is found using a formula developed by Predtechenskii and Milinskii who calculated the mean length of one story or two flights of stairs plus the landing in between them [11]. They found the length of the inclined path to be given by the following [11]:

$$L = \frac{L'}{\cos \alpha} \quad (5)$$

where α is the angle of incline of the stairs and L' is the horizontal length of the stairs. Predtechenskii and Milinskii also developed a correlation for the mean length of two flights of stairs as the following [11]:

$$L = \frac{2L'}{\cos \alpha} + 4b \quad (6)$$

where L' is the horizontal length of the stairs and b is the free width measured of the stairwell. A diagram of this mean length can be observed in Figure 4-2 below.

Rearranging equation (6) as $L' = L \cos \alpha$ and substituting this into equation (4) the length of two flights of stairs can be found as

$$L = 2L_{(3)} + 4b \quad (7)$$

where $L_{(3)}$ is the length of the stairwell calculated above using the Pythagorean Theorem or the L found in equation 6. As Building 4 has a width of 1.02 m between handrails, the length of two flights of stairs would be:

$$L = 2(3.3) + 4(1.12) = 11.08 \text{ m}$$

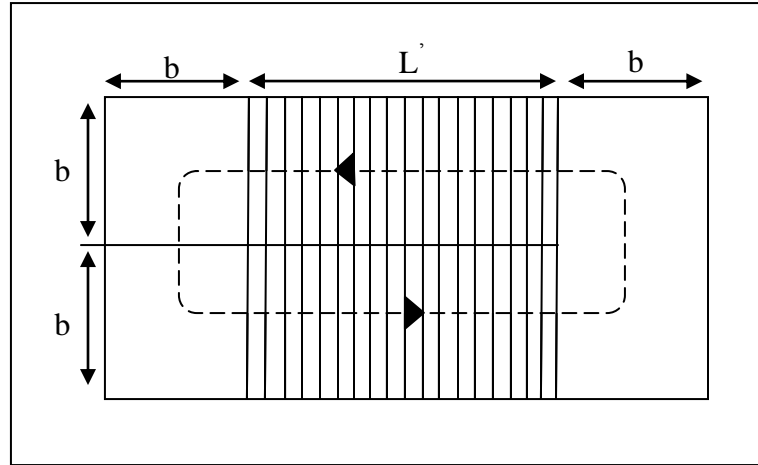


Figure 4-2: Predtechenskii and Milinskii Estimated Length for Two Flights of Stairs [11]

The NIST data was then verified by comparing the length L found above for two flights of stairs to the distance from camera to camera that is described in the next section.

4.2.2 Distance from Camera to Camera in the Stairwells

Though the length, L , was determined for two flights of stairs in the section above, the camera angles that recorded the evacuation events did not encompass both flights of stairs as indicated in Figure 3-2. NIST did not specify the exact locations of how many stairs were observed on each floor and the locations in which the entry and exit times were taken for each occupant on a particular floor. Because this camera to camera distance is an important part of the velocity calculation that will be discussed in Section 4.3, it is necessary to determine the most accurate method of measuring the distance given the data reported by NIST. An example of this data is included in the table that NIST provided for each stairwell and is presented in Table 4-1 for Building 4, Stairwell B [17].

Distance to Building Exit (m)		
Floor	When Entering View From Floor Above	When Leaving View Exiting Floor
P1	0.6624	
2	17.30	13.74
4	45.04	41.48
6	67.23	63.67
8	89.41	85.85
10	111.6	108.04
12	133.8	130.23
14	156.0	152.4
16	178.2	174.6
18	200.3	196.8
20	222.5	219.0
22	244.7	241.2

Table 4-1: Distance to Exit Calculation Given by NIST [17]

Given that occupants either entered the camera view from the floor above or they entered the stairwell on that particular floor, there could be two different enter times found in the data reported by NIST. This can be observed in Figure 3-2 in Section 3.2 where the green and yellow lines represent the two possible entrance time locations and the red line represents the exit time location. Because of this, the camera to camera distances that were calculated were based on the exit location from each camera view since every occupant had the same location where time was measured for each camera angle.

Since the distances provided by NIST were to the building exit, in order to calculate the camera to camera distances, the distances were subtracted from one view to another in the far right column entitled “When Leaving View Exiting Floor.” For instance, Floor 6 exit distance of 63.66 m would be subtracted by Floor 4 exit distance of 41.48 m to calculate the distance between leaving the camera view on Floor 6 to the camera view on Floor 4 as

$$63.67 - 41.48 = 22.19 \text{ m}$$

These calculations were then made between all the floors and this can be observed for Building 4, Stairwell B in the following table:

Distances Camera-Camera Exit to Exit (m)	
P1 to 2	13.74
2 to 4	27.73
4 to 6	22.19
6 to 8	22.19
8 to 10	22.19
10 to 12	22.19
12 to 14	22.19
14 to 16	22.19
16 to 18	22.19
18 to 20	22.19
20 to 22	22.19

Table 4- 2: Camera to Camera Distances for Exit Location of Building 4 Stair B

To verify NIST distances, the calculations from Section 4.2.1 can be considered. For Floors 24-3 it was concluded that one story or two flights of stairs had a distance based on Predtechenskii's and Milinskii's correlation of 11.08 m. Since these camera to camera distances are measuring two stories, this correlation can be multiplied by a factor of two which means the distance for two stories would be 22.16 m. As this value is very close to those calculated in Table 4-2 above for Floors 24-3, it is evident that the distances calculated by NIST are accurate.

4.2.3 Area from Camera to Camera in the Stairwells

A length measurement necessary to calculate the density throughout the stairwells was the area from camera to camera. This area calculation will be used in Section 4.4 to calculate density. In order to calculate the area, the important components are the area of the stairs themselves as well as the area of the landings.

The areas of the landings were given, and the areas of the stairs were calculated using the tread depth and multiplying this number by the number of stairs between each camera. The area varied for different buildings as the number of steps varied between floors, but in general from each camera-to-camera, there were four flights of stairs and four landings. Figure 4-3 below is a schematic of the lower portion of Stair A from Building 4. A camera is located on Floor 6, Floor 4, and Floor 2. NIST reported that there are 20 steps between each floor (with a landing in between every 10 steps) for floors 24 to 3 and then in Stair A there are 30 steps between floors 3 and 2 with two mid landings. Based on the schematic and this information, the area between Floors 6 and 4 was found by multiplying the tread depth of 0.28 m by 40 stairs and adding the area for four landings of 2.52 m. This results in an area between Floor 4 and Floor 6 of

$$A = (0.28 * 40) + (4 * 2.52) = 21.28 \text{ m}$$

Between cameras 4 and 2, there are 50 stairs and still 4 landings, because the landing at the bottom was not included in the area for the density calculation. This same calculation is repeated for all floors and varies slightly based on the number of steps that is observed in the camera view.

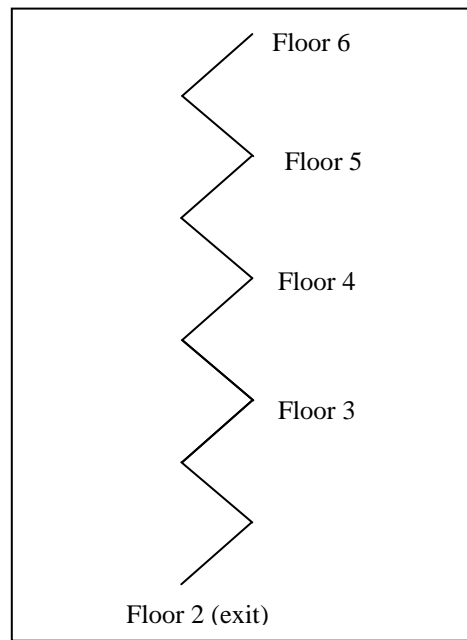


Figure 4-3: Schematic Diagram of Stair A in Building 4

4.3 Velocity Calculation

Using the distances calculated in Section 4.2.2, the local speeds for each occupant are calculated from camera to camera. To calculate the local speeds, the times that are used are the exit times from camera to camera. Similarly, the distances used in calculations are from the exit of the camera view of one floor to the exit from another floor. The exit distances and times are used for consistency. If one occupant entered on floor three and another entered on floor 4, the places that they first enter the camera view on floor 3 are different; however they will both exit the camera angle at the same point as they descend the stairs. For instance, occupant 17 is observed to enter the camera view from above the landing at 58.63 seconds on floor 6 and exit the view below the landing at 64.53 seconds. This occupant is then observed entering the camera view from above the landing on floor 4 at 86.71 seconds and exiting at 92.18

seconds. Since the exit speeds are being used to calculate the times in reference to the speed, the time that it took occupant 17 to traverse the stairs from floor 6 to floor 4 is:

$$t = 92.18 - 64.53 = 27.65 \text{ s}$$

The distance from the exiting camera view on floor 6 to the exit based on stair geometry and angle of the stair, given in the spreadsheet is 47.03 m and the distance from the exiting camera view on floor 4 to the exit is 24.84 m. This means that the distance occupant 17 traveled from floor 6 to floor 4 is

$$d = 47.03 - 24.84 = 22.19 \text{ m}$$

The speed of occupant 17 can then be calculated as

$$v = \frac{\text{distance}}{\text{time}} = \frac{22.19}{27.65} = .80 \text{ m/s}$$

The local speeds were calculated for each occupant on every floor that they came into camera view and were documented throughout the evacuation.

4.4 Density Calculation

In order to stay consistent with the locations in which the velocity was calculated, the density for each person was calculated from camera to camera. In order to calculate this, a MATLAB program was written and can be observed in Appendix A. The MATLAB code was written so that it counted the number of people from camera to camera. As with the velocities in Section 4.3 above, the exit times from each floor for each occupant helped to determine this. Since both velocity and flow are a function of density as presented in Chapter 2, how quickly a person moves is determined by the density or number of other people within the same area.

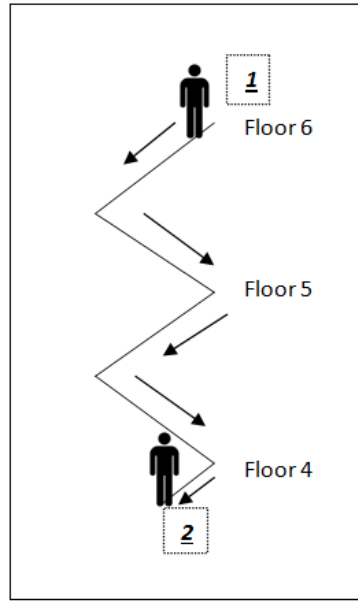


Figure 4-4: Simple Diagram of Density Calculation

The MATLAB code was written to count people. This can be observed through Figure 4-4. The code written is applied to each floor in the stairwell separately. The code first looks at the time an occupant exited the upper floor, in Figure 4-4, this would be Floor 6 at location 1. The program would then identify the time that same occupant exited the floor below, in this case in Figure 4-4, Floor 4 at location 2. The program would then count all the occupants that exited on Floor 4, at location 2 from the time the occupant exited at 1 until they got to location 2 on Floor 4. For instance if an occupant exited the stairwell on Floor 6 (location 1) 64 seconds after the alarm sounded and exited Floor 4, the next camera view below (location 2), at 92 seconds, the MATLAB code would count all the people that exited Floor 4 from between 64 seconds and 92 seconds. The MATLAB program then outputs a density calculated for each person between each camera.

The number of people that is then output using the MATLAB code was divided by the area from camera to camera calculated in Section 4.2.3 to result in a density measure in units of persons/m². It was assumed for this calculation that the density or number of people in front of the person was a good indicator for that person. This is because the occupants traveling in front of this person would influence the speed that they travel rather than any person that appears behind that particular occupant during evacuation. This density calculation also assumed that individuals were equally spaced throughout the stairwell as the entire area was used.

The MATLAB code was then run for each floor on which a camera was located in each stairwell for all of the buildings being analyzed. In order to run the MATLAB code, the exit times for each occupant were made into a text file and then it was input into MATLAB. The actual code in Appendix A had to be modified for each building as the P in the second line of the code represents the number of people in the stairwell. Then the column variables had to be changed with each run for each camera to camera calculation based on the columns that the data for that floor was uploaded in the text file.

4.5 Flow Calculation

Specific flow rates were calculated based upon the equation presented by equation 5 in Section 2.3 and was taken from the SFPE Handbook [4]. The density calculated in the previous section for each occupant between floors was multiplied by the corresponding velocity of that person between each floor (camera view). For example the velocity was determined by an occupant between Floors 6 and 4 based on the time it took them and the distance they traveled and this was multiplied by the

density from Floor 6 to Floor 4 that was in front of them. By using this method of $S \cdot D$ (speed times density), the specific flow was calculated for each occupant between each camera view that they traveled.

Chapter 5: Results and Discussion

Each of the stairwells was first analyzed individually. Each stairwell was examined to understand how each occupant behaved and looked at the occupants in the stairwell versus both velocity between each floor as well as the local density between each floor. Each stairwell was then graphed with the local density versus the local velocity to examine the relationship between these two variables. A trendline was then applied to these graphs both normally as well as after the 0.5 person/m^2 value in density to stay consistent with the beliefs that density does not affect velocity before this value. An example of one stairwell is provided in the following chapter, while the rest of the data can be found in Appendix B.

The movement speeds as well as the density throughout the stairwells were then examined to look at how all the stairwells behaved in comparison to each other. The stairwells were then separated and grouped by similar tread width and riser height dimensions in order to stay consistent with the correlations developed by Nelson and Mowrer in the SFPE Handbook. The density versus speed of occupants in the stairwells with similar dimensions as well as density versus specific flow in the stairwells was graphed separately with the Nelson and Mowrer correlation. There is one example of each graph in the following chapter and the rest can be found in Appendix C.

The specific flow for all the stairwells was then broken down by density ranges of 0.5 person/m^2 to look more closely at how the occupants traveled within the stairs. The averages were then calculated for each effective stair width grouped by the same density ranges mentioned previously.

This data that was analyzed examined only the enter and exit times of occupants. There were a few components that were not included in this analysis but may have an effect on how occupants moved throughout the building as analyzed by Jessica Kratchman in her thesis in 2007 [15]. It did not take into consideration components of human behavior such as whether occupants were carrying something, whether individuals were passing one another or whether they might be staying in line behind someone moving at a slower pace. It also did not take into account gender as this was an average office building population.

5.1 Stairwells Analyzed Individually

Each of the stairwells were initially analyzed individually. The occupant number, or the number given to each occupant in the order they exited the building on the bottom floor, was graphed versus both local velocity throughout the building as well as density. The lower occupant numbers were the individuals that exited the building first and the later occupant numbers correspond to the individuals that exited the building toward the later portion of the evacuation. A graph of occupant versus velocity for stairwell 5B can be observed in Figure 5-1 and occupant versus density in Figure 5-2 for the same stairwell. The velocities in Figure 5-1 are the local velocities

calculated from floor to floor in Section 4.3.

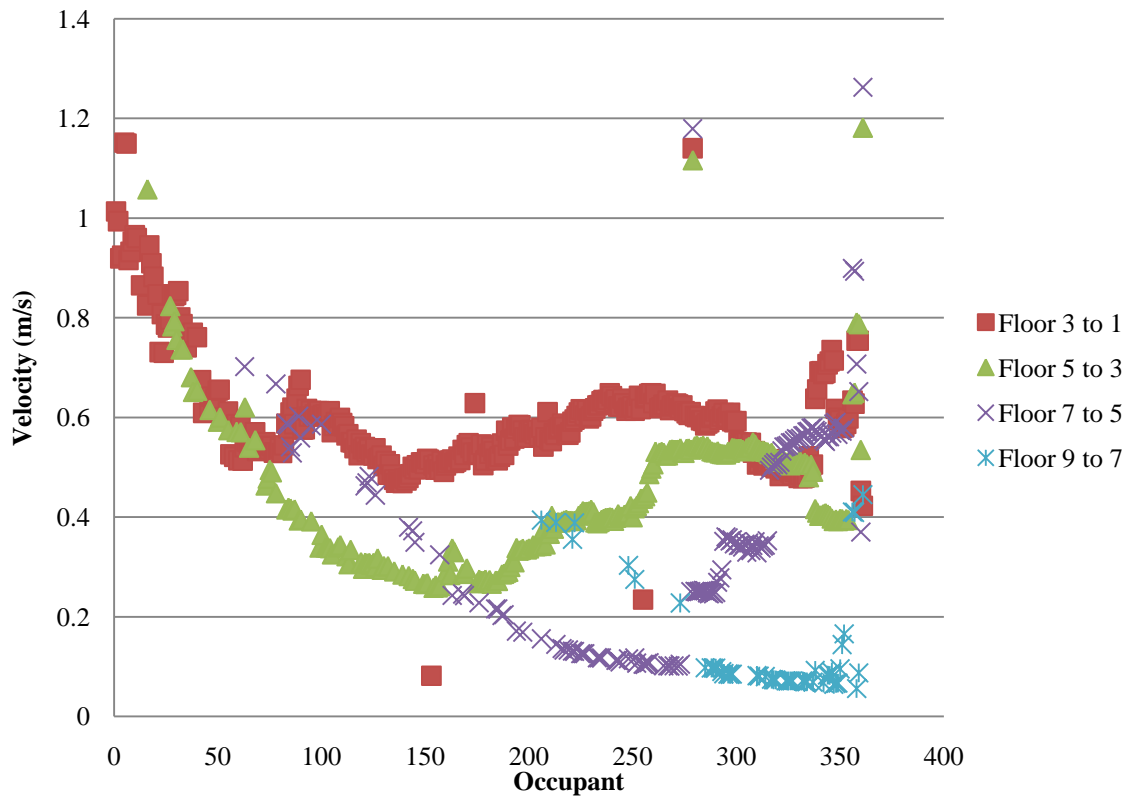


Figure 5-1: Stairwell 5B Occupant versus Local Speed

Figure 5-1 above depicts the occupants and the local velocities that they traveled throughout the building floor to floor until they exited on Floor 1. For instance those individuals around occupant 350 had very low velocities on the upper floors in the stairwell, about 0.1 m/s. However, these same occupants traveled faster on the lower floors around 0.7 m/s. This graph and similar graphs found in Appendix B for other stairwells seem to follow a trend where occupants have higher velocities initially, the velocities then decrease and level out and then near the end of the evacuation (high occupant number) the velocities of the occupants increase again.

This is due to the fact that initially when the occupants in the beginning entered the stairwell they were able to travel faster than during the middle of the evacuation.

Since Figure 5-1 is simply the velocities of the occupants, it is necessary to really understand what might be causing them to speed up or slow down. In order to understand what densities that the occupants may be experiencing, the occupant number versus the local densities calculated in Section 4.4 were graphed for each stairwell. Figure 5-2 displays the occupant versus the local densities for the same stairwell examined in Figure 5-1 and Appendix B has the corresponding graphs for the other seven stairwells analyzed.

Figure 5-2 can be analyzed to understand how crowded this stairwell becomes throughout the evacuation. It is evident from the figure, and the other stairwells in Appendix B seem to follow the same trend that the stairwell is initially not very dense, the density increases until it reaches a maximum density for that particular floor and then the density decreases until there are again not many people in the stairwell. This trend can be observed for all four of the floor to floor densities graphed below. This means during the initial evacuation there weren't that many people in the stairwell, as time went on the number of occupants in the stairwell increased to a maximum point where there were not many new occupants entering the stairwell and then the number of people between floors decreased as evacuation continued and people continued to exit the building.

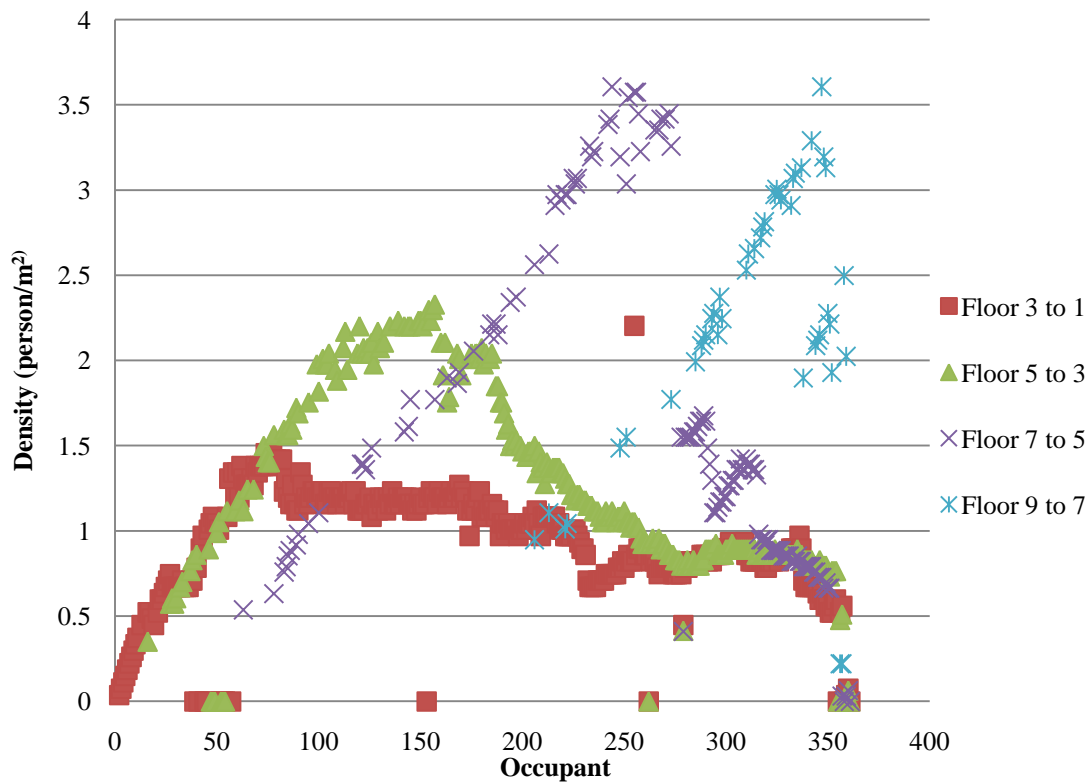


Figure 5-2: Stairwell 5B Occupant versus Density

Figures 5-1 and 5-2 can then be examined simultaneously to understand the impact of density on an occupants' velocity in between floors inside of the stairwell. For example, in Figure 5-2 above, from Floor 5 to Floor 3 there is an increasing density until about 2.25 person/m² which occurs around occupant 150. Figure 5-1 depicts a decreasing speed between the same floors until occupant 150. This demonstrates that between these floors there is an increase in density. This has resulted in a decreased velocity since an increase in the number of people surrounding an occupant means that there is more congestion and thus they descend the stairs at a slower pace. To get a clearer picture of how density and velocity impact one another inside of the stairwell, a graph of local density versus local velocity was graphed for

each stairwell. Figure 5-3 below shows this relationship for Stairwell 5B and the equivalent graphs for the other seven stairwells can be found in Appendix B. Figure 5-3 shows that there is in fact a linear relationship between the two quantities of velocity and density in the stairwell. In Figure 5-3 as the density increased throughout the stairwell in between floors, the velocity of occupants decreased. However, it is apparent by the actual trend-line and R^2 value of 0.75 that it is not an exact linear relationship but instead a trend which shows that the velocity is inversely proportional to the density in the stairwell. The trend-line in these graphs did not include the first 0.5 person/m² to be consistent with the SFPE Handbook which considers this low density to not have an impact on the velocity experienced.

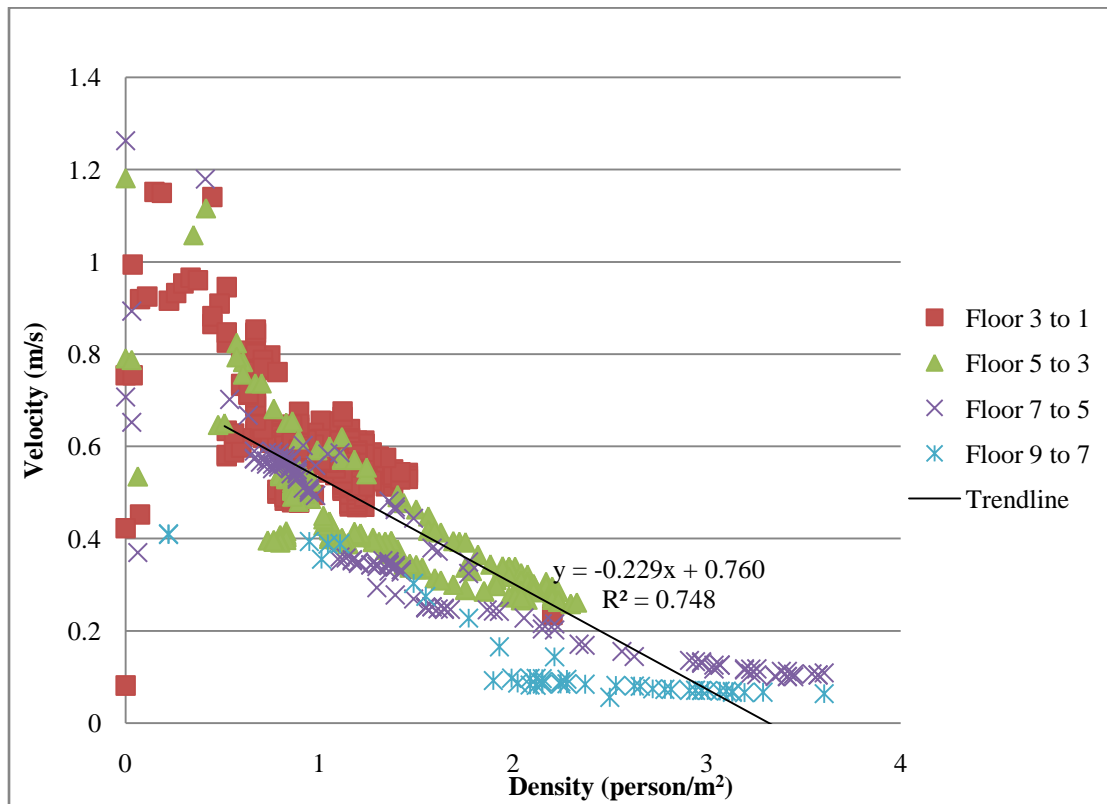


Figure 5-3: Stairwell 5B Density versus Velocity

5.2 Movement speeds

The maximum, minimum and average velocities observed in each of the stairwells are reported in Table 5.1. The average velocity reported in Table 5.1 is the average of all the local speeds from floor to floor that have been calculated throughout the stairwell not the average speed for an occupant to descend the stairwell. The stairwells in Table 5.1 are presented in order of smallest to largest effective stairwell width, with all three stairwells in building 7 having an effective width of 0.73 m, and buildings 4, 5, and 8 having effective widths of 0.82 m, 0.97 m, and 1.08 m respectively. It is interesting to note that Building 8 with the largest effective width is not the stairwell with the greatest average velocity. This may have occurred for numerous reasons including high density in the stairwell but it is still interesting to note that this building did not have the greatest average velocity. However, there is a lot of variation in terms of velocity in the stairwells, as indicated by the standard deviation of 0.2 m/s for every building except Building 8 as indicated in Table 5-1. This standard deviation is very high since the majority of buildings averaged between 0.4 and 0.6 m/s which is reported in Table 5-1 below. This means that one standard deviation was between 30-50% of the average. The average velocities reported in Table 5-1, ranging from 0.4-0.6 m/s, are close to the optimum speed for occupants traveling down stairs quoted in the SFPE Handbook by Proulx as 0.5 m/s [16].

Stairwell	Effective Width	Velocity (m/s)			
		Minimum	Maximum	Average	Standard Deviation
7-1	0.73	0.097	1.195	0.421	0.159
7-3	0.73	0.116	1.392	0.487	0.162
7-7	0.73	0.106	1.187	0.370	0.205
4A	0.82	0.089	1.320	0.568	0.179
4B	0.82	0.194	1.431	0.570	0.166
5A	0.97	0.081	1.281	0.475	0.167
5B	0.97	0.056	1.179	0.481	0.185
8	1.08	0.012	1.415	0.508	0.135

Table 5-1: Table of Maximum, Minimum, Average, and Standard Deviation of Velocities in the Stairwells

Figure 5-4 depicts the data from all of the buildings in which data was collected and examines the density versus the velocity for all of the buildings. One is able to better understand the values presented in Table 5-1 by examining this graph that depicts the minimums, maximums, and the averages for all the stairwells, or where most of the data falls on the graph. This data will be analyzed separately in the following sections, however it is interesting to see the variation in speeds observed throughout all the stairwells. Though it seems to follow a downward sloped trend, there is a lot of variation that exists throughout all of the buildings. For example, if one were to examine the density of 1.0 people/m^2 there is a wide variation in the velocities ranging from about 0.1- 0.8 m/s throughout all the stairwells.

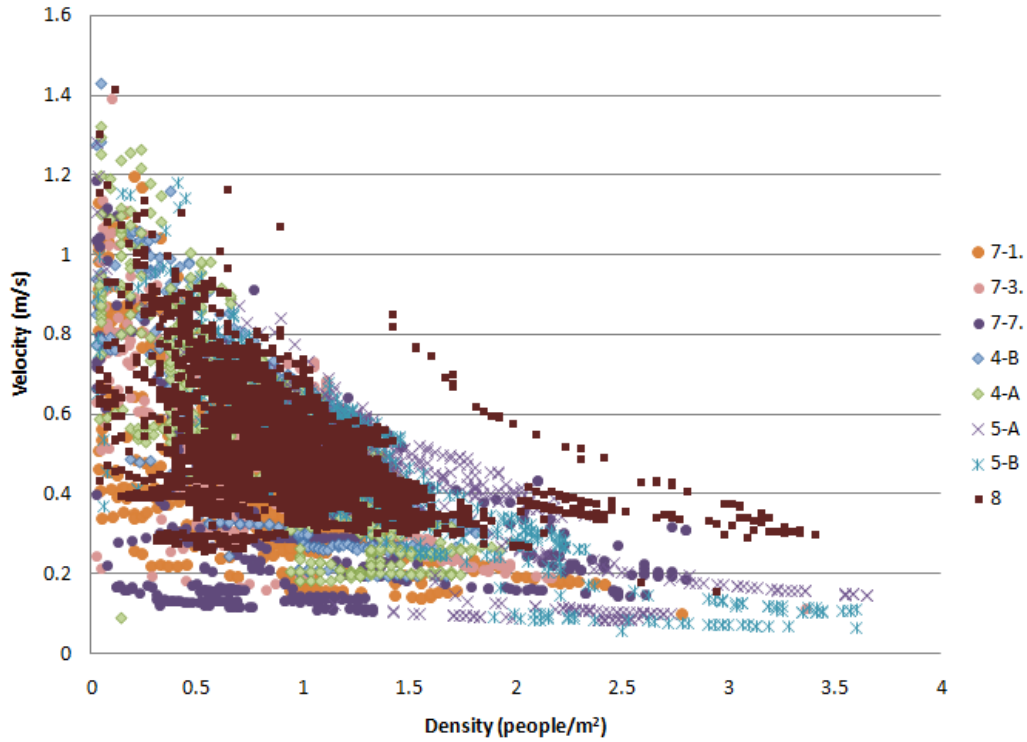


Figure 5-4: Density versus Velocity for all Stairwells

5.3 Density in Stairwells

The minimum, maximum, and average densities that were observed in the stairwells as well as the standard deviation can be observed in Table 5-2.

Stairwell	Density (persons/m ²)			
	Minimum	Maximum	Average	Standard Deviation
7-1	0.041	2.788	0.948	0.374
7-3	0.025	3.363	0.886	0.385
7-7	0.019	2.790	1.067	0.580
4A	0.037	1.976	0.906	0.332
4B	0.023	1.861	0.994	0.304
5A	0.032	3.653	1.329	0.580
5B	0.032	3.605	1.240	0.653
8	0.035	3.402	0.979	0.530

Table 5-2: Maximum, Minimum, Average and Standard Deviation of Densities in the Stairwells

Although the velocities seem to vary with stairwell width, the average density in each stairwell was on the same order of approximately 0.9-1.0 person/m². As with the velocities, the standard deviation seems to be also large as 40-60% variation on the mean is one standard deviation. Some of the maximum densities that occurred in the stairwells are approximately 3.6 persons/m², with the minimums being about 0.02-0.04 m/s. Based on the correlations in the SFPE Handbook, at a density of 3.8 persons/m², people should be unable to move in the stairwell [4]. While this correlation is an engineering equation and therefore meant to be conservative it is still interesting to note that people are still moving at high densities. They are moving slowly, around 0.1 m/s but are still moving. This can be observed in Figure 5-4 in Section 5.2 above comparing the densities to the speed of movement by individuals.

5.4 Density versus Velocity in Stairwells

The correlation between the speed an occupant moves down the stairs was presented as equation 4 in Section 2.3 from Nelson and Mowrer's chapter in the SFPE Handbook. This correlation indicates that the velocity should be linearly proportional to the density that the occupant experiences. Coefficients in the correlation depend on the riser height and width. The riser height and tread depth for each stairwell as well as the k-value used in equation 4 to obtain the SFPE velocity correlation is presented in Table 5-3 below.

Stairwell	Riser (m)	Tread (m)	k value
7-1	0.19	0.25	1.00
7-3	0.19	0.25	1.00
7-7	0.19	0.25	1.00
4A	0.18	0.28	1.08
4B	0.18	0.28	1.08
5A	0.18	0.28	1.08
5B	0.18	0.28	1.08
8	0.18	0.25	1.08

Table 5-3: Stairwell Riser Height and Tread Depth and Corresponding k-value for Nelson and Mowrer Correlation

The relationship of velocity versus density for the four stairwells (4A,4B, 5A, 5B) with a tread depth of 0.28 m and a riser height of 0.18m is indicated in the graph presented in Figure 5-5 and are compared to this SFPE correlation. Trend-lines were also added for each stairwell and are indicated in this figure as well as the equation for the line for the corresponding stairwell. None of the four stairwells closely follow the correlation presented by Nelson and Mowrer since three of the four stairwells have R^2 values ranging from 0.6 to 0.7, while one has a value of 0.2. This indicates a substantial amount of variance, especially for stairwell 4B. Also, recalling the standard deviation found in Section 5.1, Stairwell 4B, 5B, and 5A have the same slope as the SFPE correlation and the velocity would be closer if one positive unit of standard deviation was added to this line. By examining this graph it appears that the trend is that the SFPE correlation is an upper bound on the data from these four stairwells.

A corresponding graph has also been developed for Stairwell 7-1, 7-3, and 7-7, which have a tread depth of 0.25 m and a riser height of 0.19 m. This graph is included in Appendix C, along with the graph for stairwell 8 (each graph also depicts

the Nelson and Mowrer correlation). The stairwell in Building 8 has a tread depth of 0.25 m and a riser height of 0.18 m. As there is no constant for this specific dimension, the SFPE correlation was applied with a constant for a stairwell with dimensions of 0.28 by 0.18 m, as these were the closest to the dimensions of the stairwell in Building 8.

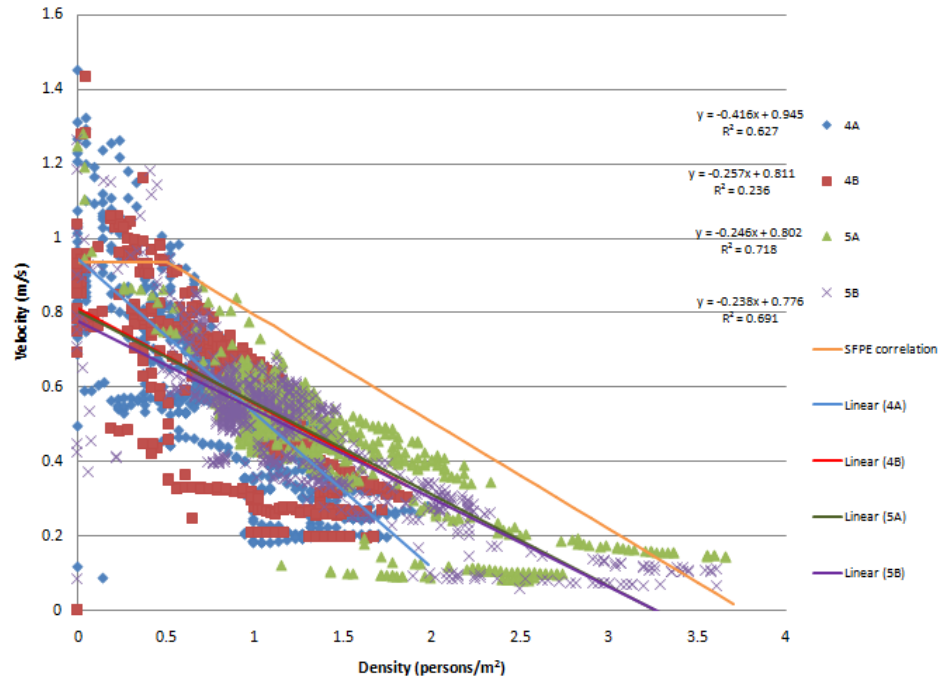


Figure 5-5: Velocity versus Density for 0.28 by 0.18 m stairs

Considering all three velocity graphs, the same trend is apparent. With increasing density, there is a decrease in velocity throughout the buildings. However, while the velocities are decreasing, the data is still very noisy, with an appreciable variation in speed evident for a particular density as opposed to the linear correlation that is outlined by Nelson and Mowrer in the SFPE Handbook [4]. It is important to note this wide variation that is observed throughout the data as some densities the range is about 0.6 m/s which is a large discrepancy. Although it does not match the Nelson and Mowrer correlation directly, the trend does seem to be linear and the

Nelson and Mowrer correlation also appears as an upper bound in the data as most of the data appears under this correlation. The Nelson and Mowrer equation is an engineering equation and though it is derived from many different data sets, it is interesting that the equation should be conservative and thus a lower limit on the data as opposed to an upper limit which can be observed from Figure 5-5.

5.5 Density versus Specific Flow in Stairwells

The minimum, maximum, and average specific flows that were observed in the stairs as well as the standard deviation are presented in Table 5-4. These were calculated using equation 5 in Section 2.3, where the specific flow is the product of the density and speed of a person traveling through the stair.

Stairwell	Specific Flow (p/s-m effective)			
	Minimum	Maximum	Average	Standard Deviation
7-1	0.018	0.672	0.361	0.126
7-3	0.006	0.766	0.401	0.166
7-7	0.010	0.915	0.363	0.218
4A	0.013	0.699	0.468	0.140
4B	0.019	0.719	0.529	0.137
5A	0.035	0.870	0.549	0.150
5B	0.021	0.790	0.496	0.136
8	0.015	1.207	0.464	0.176

Table 5-4: Minimum, Maximum, Average, and Standard Deviation Specific Flows

Specific flow should be independent of stair width, however the Table 5-4 demonstrates that as stairwell width increases, the average specific flow is also increasing slightly. The standard deviation is on the same order between 0.1 and 0.2 person/s/m effective width for all the stairwells so this does not seem to have an effect on the increasing specific flow.

Because the specific flow calculation takes into account the speed an individual is traveling and the density, the tread and riser dimensions cause the correlation to be slightly different for stairs of different dimensions. As in Section 5.3, the specific flow for stairwells with the same dimensions was graphed together on a graph of density and specific flow. Nelson and Mowrer's correlation was also included to examine whether the theory holds true for the data analyzed by this research. Figure 5-6 depicts the specific flow versus the density for stairs that had riser heights of 0.18 m and tread depths of 0.28 m. Nelson and Mowrer's correlation in the SFPE Handbook is the uppermost curve and each data set from each building was fitted with a square polynomial curve [4]. The trend-line equation can be observed next to the legend of the building it coincides with. Overall, the trend-lines were able to accurately predict the outcomes as the trend-lines for three of the four buildings had R^2 values on the order of 0.9. However, neither the data nor the trend-lines seem to match the SFPE correlation as their flow rate is lower than the one predicted by SFPE. Similar to the density versus velocity graphs in the previous section, the Nelson and Mowrer correlation should be conservative as it is an engineering equation, but instead it serves as the upper limit on the data.

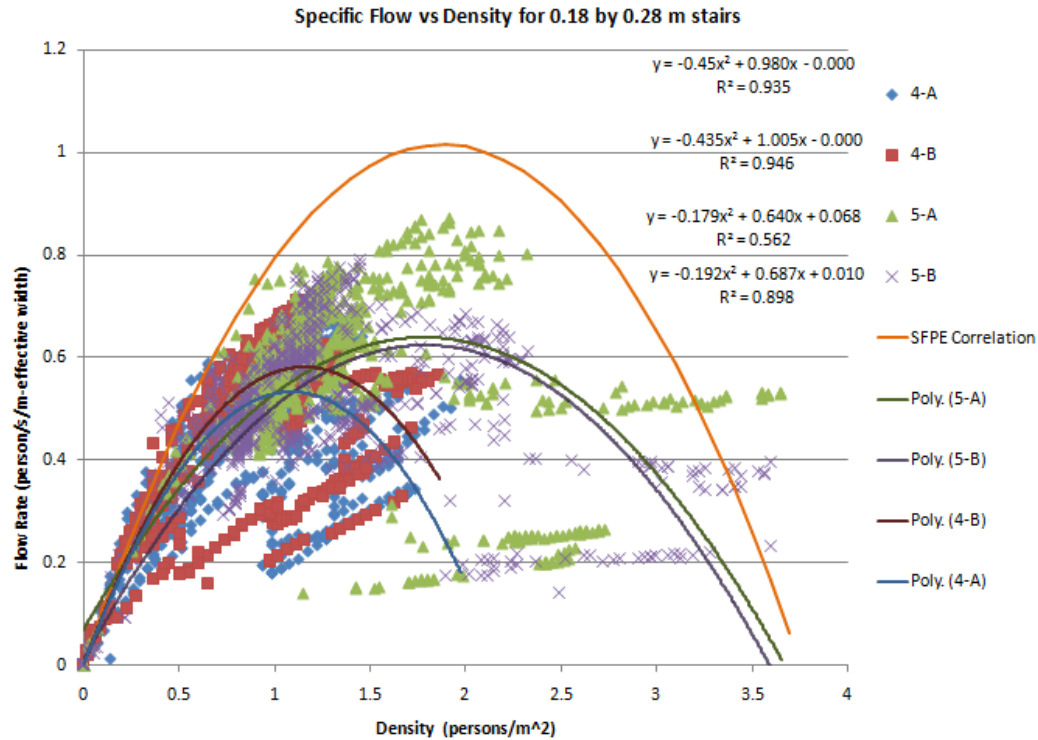


Figure 5-6: Specific Flow Rate versus Density for 0.18 by 0.28 m stairs

Though specific flow should also be independent of stair width, Building 4 has a smaller effective width than Building 5 and people seem to have a smaller specific flow rate thus moving at a slower pace in Building 4 based on the trend-line. The trend-line for both stairwells in building 5 portray the same notion that a density of about 2 person/s/m-effective width would be optimum and occupants would be traveling the fastest at this point. A graph similar to Figure 5-6 was also developed for the three stairwells that have dimensions of 0.19 m by 0.23 m and for the stairwell with dimension 0.18 m by 0.25 m.

As noted in the previous section, the data observed during the movement of stairs is varied. For a particular density, there are a range of flow rates that occur within a given staircase. This does not agree with the assumption made in the SFPE Handbook in which every density has a corresponding flow rate. It is noted that

similar to Figure 5-5 and the graphs described in Section 5.4 the correlation by Nelson and Mowrer in the SFPE Handbook acts as an upper bound on the data in Figure 5-6 thus not the conservative engineering equation that it was meant to be.

The graph of specific flow versus density for the building of 0.18 m by 0.25 m has interesting behavior. When the building reaches 2 persons/s/m-effective width, the SFPE correlation reaches the maximum flow and as density increases, flow rate decreases. This building has the opposite effect in that after the critical value of 2 persons/s/m-effective width the density continues to increase and the flow rate of a few occupants continues to increase.

Since the question concerning specific flow in stairwells of different effective width was the basis for this research, the specific flow versus density was examined in more detail. The densities were divided into sections and a separate graph of specific flow was made for every 0.5 person/m² of density. A graph of the range 0.5 person/m² through 1.0 person/m² can be seen in the graph in Figure 5-7.

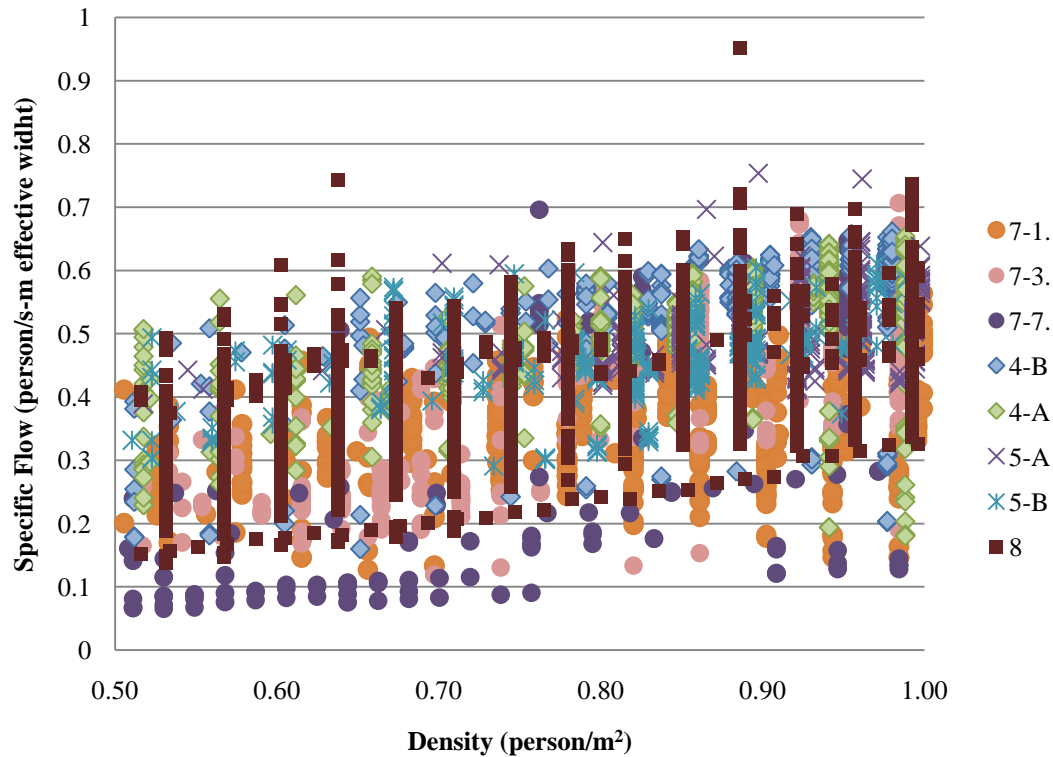


Figure 5-7: Density versus Specific Flow for Density Range 0.5-1.0 person/m²

The corresponding range of densities from 0.0-2.0 person/m² can be found in Appendix D. When the specific flows from all the stairwells appear on the same graph it is interesting to note that the occupants seem to have a higher specific flow in stairwell 8 which has the greatest effective width than stairwells 7-1, 7-3, and 7-7 which have the lowest effective width.

5.6 Average Velocities and Specific Flow of Stairwells Separated by Densities

In order to be able to analyze if individuals were moving faster in some stairwells over others, the average velocities and specific flows were calculated using the density ranges that were examined in Figure 5-7 as well as graphs in Appendix D.

These results can be observed in Table 5-5 and 5-6 for velocity and specific flow respectively.

Stairwell	Effective Width (m)	0.0-0.5 (person/m ²)	0.5-1.0 (person/m ²)	1.0-1.5 (person/m ²)	1.5-2.0 (person/m ²)	average standard deviation
7-1	0.73	0.648	0.445	0.356	0.224	0.129
7-3	0.73	0.642	0.478	0.472	0.247	0.118
7-7	0.73	0.466	0.353	0.388	0.275	0.198
4A	0.82	0.817	0.608	0.453	0.247	0.115
4B	0.82	0.840	0.631	0.492	0.313	0.115
5A	0.97	0.928	0.562	0.517	0.351	0.111
5B	0.97	0.849	0.578	0.492	0.304	0.126
8	1.08	0.624	0.541	0.457	0.398	0.129

Table 5-5: Average Velocities in Stairwells Separated by Density Ranges

Stairwell	Effective Width (m)	0.0-0.5 (person/m ²)	0.5-1.0 (person/m ²)	1.0-1.5 (person/m ²)	1.5-2.0 (person/m ²)	average standard deviation
7-1	0.73	0.139	0.355	0.426	0.366	0.096
7-3	0.73	0.185	0.384	0.526	0.418	0.093
7-7	0.73	0.093	0.286	0.458	0.492	0.158
4A	0.82	0.231	0.501	0.517	0.404	0.099
4B	0.82	0.238	0.553	0.558	0.523	0.100
5A	0.97	0.219	0.505	0.619	0.605	0.132
5B	0.97	0.213	0.464	0.588	0.525	0.116
8	1.08	0.217	0.409	0.547	0.656	0.126

Table 5-6: Average Specific Flows in Stairwells Separated by Density Ranges

Since specific flow takes into account both speed and density, attention was focused on Table 5-6 addressing the specific flow. The average was then taken for all the stairs with the same effective width. From these calculations, there was then one average specific flow for each stairwell of the same effective width and each density range. This table can be observed in Table 5-7 below.

Effective Width (m)	0.0-0.5 (person/m ²)	0.5-1.0 (person/m ²)	1.0-1.5 (person/m ²)	1.5-2.0 (person/m ²)	average standard deviation
0.73	0.139	0.342	0.470	0.425	0.116
0.82	0.234	0.527	0.538	0.463	0.099
0.97	0.216	0.484	0.603	0.565	0.124
1.08	0.217	0.409	0.547	0.656	0.126

Table 5-7: Average Specific Flows for Each Effective Width Separated by Density Ranges

In order to see these results more effectively, they were then graphed with one standard deviation. This graph can be observed in Figure 5-8.

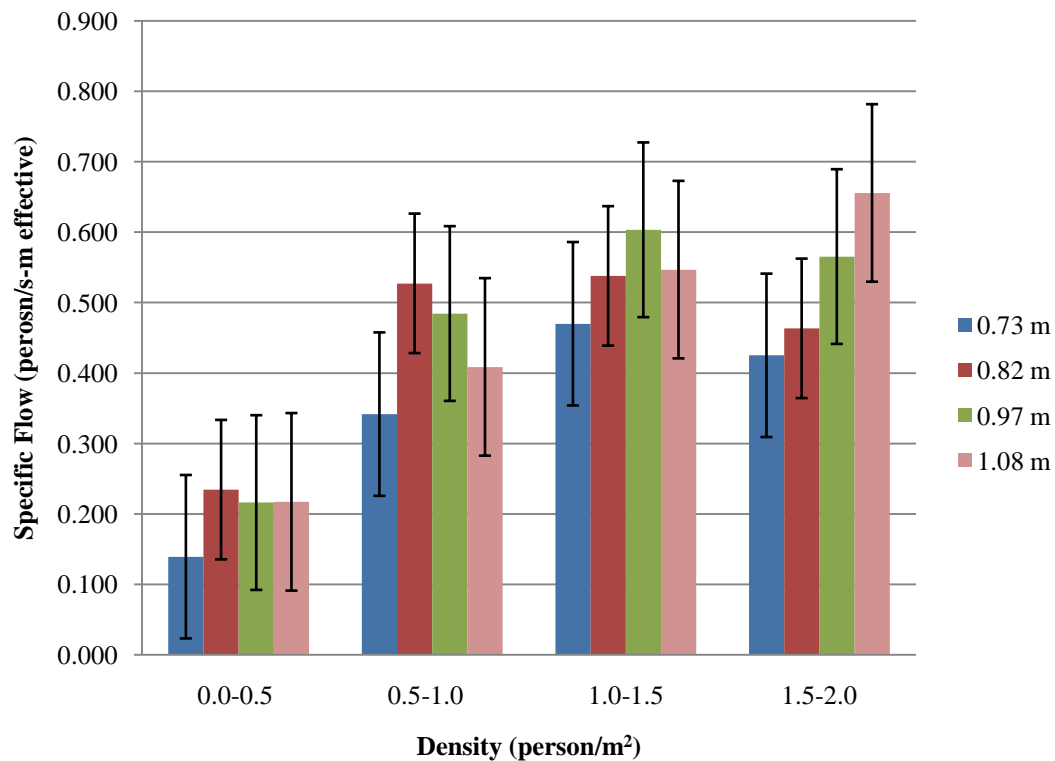


Figure 5-8: Average Specific Flow for Each Effective Width Grouped by Density Ranges

This graph helps to show how varied the specific flows are for each grouping of effective width and densities. The lowest effective width of 0.73 m has the lowest specific flow in each density grouping. Since specific flow takes into account

effective width, these averages should be closer together and more normalized. It shows the variation that exists between the different effective widths within the stairwells.

Chapter 6: Summary and Conclusions

The purpose of this research was to determine whether the effective width of a stairwell had an effect on both the specific flow of occupants in a stairwell as well as the velocity by the occupants. This work was done in order to help the evacuation community better understand the current population and how they move throughout building evacuations. As mentioned in Chapter 2, much of the data that exists concerning people movement on stairwells as well as the engineering equations developed by Nelson and Mowrer in the SFPE Handbook is based on evacuations observed a few decades ago. The current society is getting older with the baby boomer generation getting closer to retirement age and the obesity epidemic is increasing. This leaves the current U.S. population having much different demographics than the data collected thirty years ago.

The findings of this research could potentially impact engineering calculations of evacuation times that impact stairwell width. Chapter 5 shows that many occupants throughout the stairwells have a lower velocity and specific flow as that which is predicted by the existing engineering equations. This means that people are moving slower than what is predicted and thus could take a longer time to exit during an evacuation. These speeds and specific flows would also impact evacuation simulation tools and the calculations that are made within them for movement within a stairwell. It could also impact the way that density is calculated within the simulation events which in turn would impact specific flow.

This research analyzed data that was collected by NIST from eight different stairwells during four building evacuations. The spreadsheet that summarized the

evacuation data included enter and exit times for each occupant based on cameras on every other floor. From the spreadsheet data, the velocity and density between cameras (approximately every other floor) was determined for each occupant throughout the stairwells. Using these values, the specific flow was calculated for each occupant as they moved throughout the stairwell. The densities, velocities, and specific flows were then compared together and a trend-line was found for each of these graphs.

The data was then separated by riser height and tread width and these values were graphed together and compared to Nelson and Mowrer's correlation from the SFPE Handbook. The average velocities and specific flows for each stairwell were also determined but these values were broken into density ranges exploring every 0.5 person/m².

6.1 Velocity vs Density

Similar trends were identified in all of the stairwells where as density increased, the speed of the occupants slowed. However, none of the data that was analyzed directly matched the SFPE correlation for density and velocity. This correlation developed by Nelson and Mowrer seems to be an upper limit on the majority of the data, as virtually all of the data is below this linear equation.

In general, the outcome of the velocity data was very noisy and shows the influence of human behavior where people do not behave identically throughout the evacuation. There was also variation in that for the same density conditions, some occupants moved down the stairs at a greater velocity than others. It also seems that in buildings that have a larger effective width, people travel slightly faster.

6.2 Specific Flow Rates on Stairwells of Different Widths

The specific flow rates of individuals during evacuation followed the parabolic shape that is consistent with the SFPE Handbook in which the specific flow rates increased to a maximum as densities increased, then decreased as more occupants entered the stairwell. However, the SFPE Handbook predicted the specific flow rates to be much greater than the ones observed. Similar to the Nelson and Mowrer velocity correlation, the specific flow rate correlation acted as an upper limit on the majority of the data.

The stair with the largest effective width, stairwell 8 did seem to follow the parabolic trend more closely than other stairwells. It was also evident through these calculations that human behavior or another factor besides stairwell width came into play as there were numerous flow rates for a particular density as opposed to the linear relationship presented in the SFPE Handbook.

6.3 Summary of Findings

Overall the data that was collected by NIST and analyzed was extremely noisy. Even when smoothed out and averaged, the specific flow rate which should be independent of stair width seemed to be influenced by it. As noted in Figure 5-7, the stairwells that had larger effective widths generally produced larger specific flow rates.

Density did affect how people moved in that there were trends between density and velocity and density and specific flow but there was still a wide range of both specific flows as well as velocities for any particular density. A linear trend was definitely observed from the results of this research between speed and density as

well as a parabolic trend between density and flow rate. However, due to human factors or other areas not within the scope of this project, a good correlation to depict these relationships was not found. One of the interesting findings is that the engineering correlations developed by Nelson and Mowrer in the SFPE Handbook both for velocity and specific flow acted as upper bounds on the data that was collected.

6.4 Future Research

In the future, more research needs to be completed to try to explain the wide variance in both velocity and flow rates for particular densities. The large variance could be attributed to several parameters which have not been considered in this research project such as

- An individual's position on the stairs
- The gender of the occupant
- How density was calculated in this project

The position of an individual on the stairwell might make a difference in how fast they moved down the stairs. For instance, one could examine whether an individual has a higher specific flow rate if they travel on the inside of the stair versus the outside of the stair, as it takes less time for a person to travel around the inside then to walk all the way around a landing to stay on the outside of the stair.

Gender may play a role in the evacuation from buildings. One could examine whether at a similar density does one gender, either men or woman seem to travel faster when there are more people around them in the stairwell.

The way density was calculated in this research may influence the results of the data. In this research density was measured over a large area, usually being about two flights of stairs. Since density is such a big factor in the velocity and specific flow rate equations, future research could be conducted to see whether measuring the number of people over a smaller area would produce results that are closer to the SFPE Handbook correlation or seem to be similar to the results in the previous sections. Future research could also be conducted to determine the different ways that density could be measured given the data from NIST. It would be interesting to look at where density is measured corresponding to each individual person and whether measuring the density around the person (in front and behind) is more accurate than measuring the density of the individuals in front of them during the evacuation.

Future research could also be examined in terms of conducting the actual building evacuation. One could try to determine if there is there an optimal place to put the camera in order to conduct more accurate results. For instance in relation to this research, placing a camera on every floor as opposed to every other floor would have decreased the distance over which one was measuring velocity as well as density and flow rate and may have produced more accurate results since the values would be between one floor as opposed to two.

This data collected by NIST is the first being officially released in terms of numerous large scale building evacuations. In order to better understand the data they collected as well as future data they will collect, a discussion of the most accurate

way to analyze it to produce the best results would be invaluable to future researchers who want to use the data.

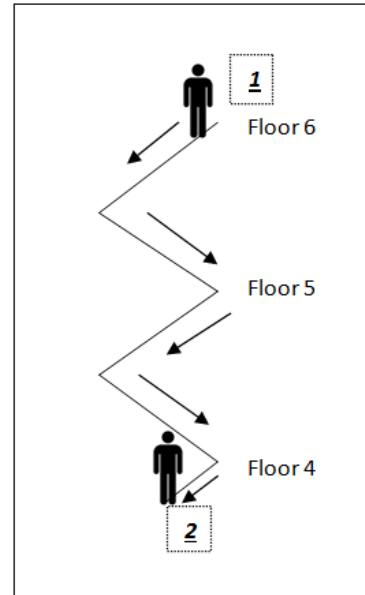
The findings of this research could potentially impact engineering calculations, simulation tools, as well as code development. As discussed in Chapter 5, virtually all occupants throughout the stairwells have a lower velocity and specific flow than what is predicted by the engineering equations developed by Nelson and Mowrer. This means that people are moving slower than what is predicted and thus could take a longer time to exit during an evacuation. These speeds and specific flows would also impact evacuation simulation tools. Currently, none of the tools are based on the speeds and specific flows that were calculated as a part of this research. Also the calculations that are made within the simulation tools for movement on a stairwell do not include any of the recent data analyzed in this research. The way density was calculated for this research has not been used before and if this is found to be the best way to calculate density it could impact the calculation of density in the tools would impact specific flow. This research could also impact codes since occupants were found to move slower this might impact the minimum effective width for stairwells as they should be wider in the event that stairwells increase in density.

Appendix A: Matlab Code for Density

See Section 4-4 for detailed description of density calculation

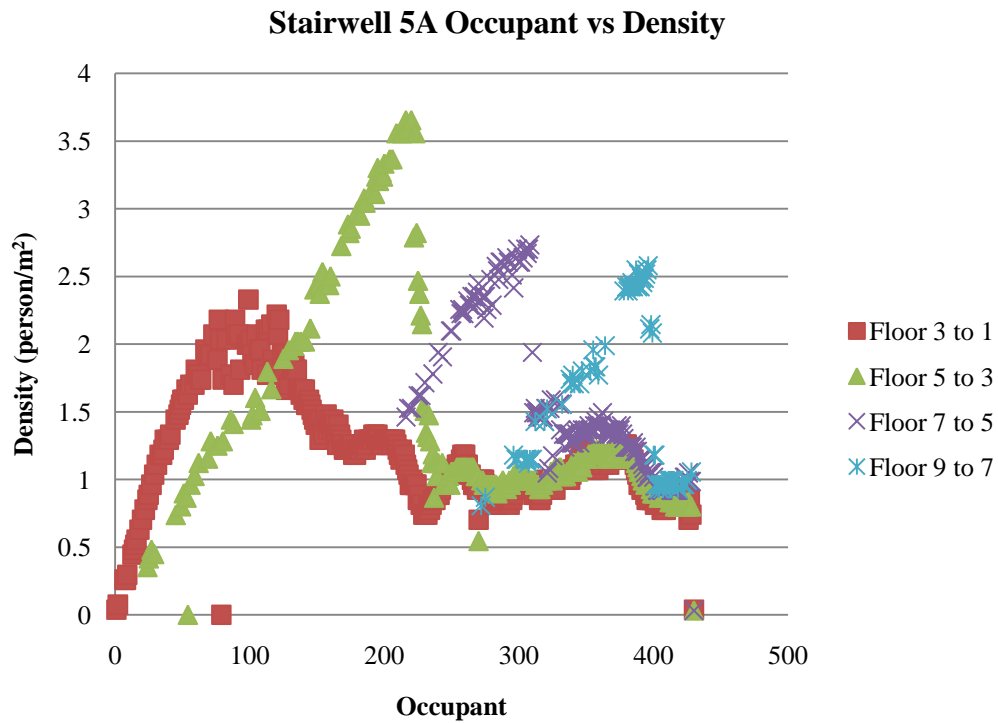
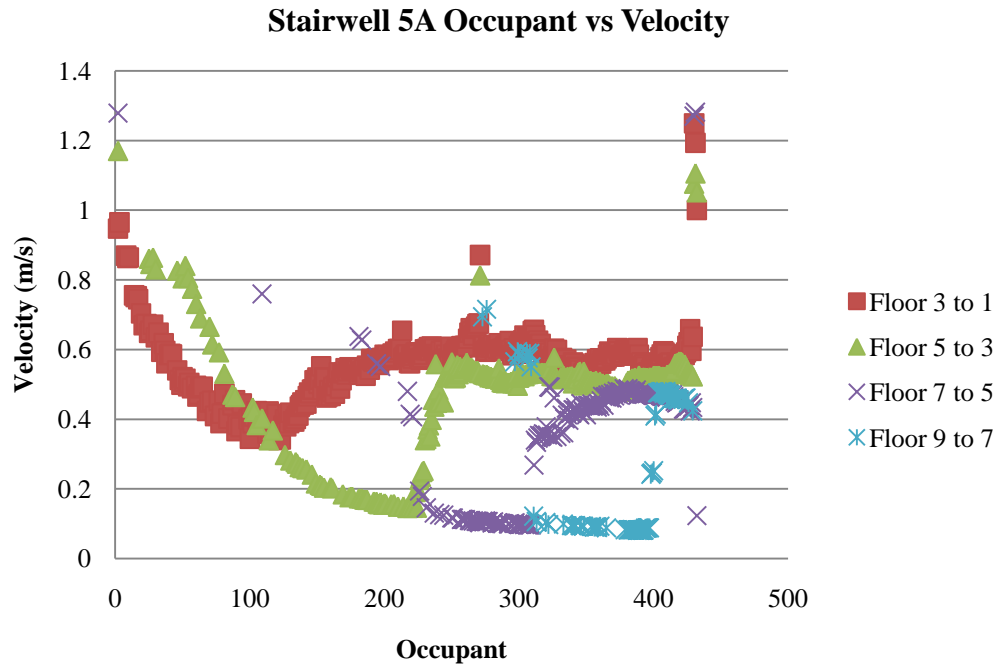
```
A=data;
P=432;
A(isnan(A)) = 0;
for k=1:1:P;
    j=1;
    for i=1:1:P;
        if ((A(i,2)<(A(k,2)) && (A(i,2)>(A(k,3)))))
            if A(k,3)==0
                N(j)=0;
                j=j+1;
            elseif A(k,3)~=0
                N(j)=1;
                j=j+1;
            end
        end
    end
    if j~=1
        People(k)= sum(N);
        clear N
    elseif j==1
        People(k)= 0;
        clear N
    end
end

People=People'
```

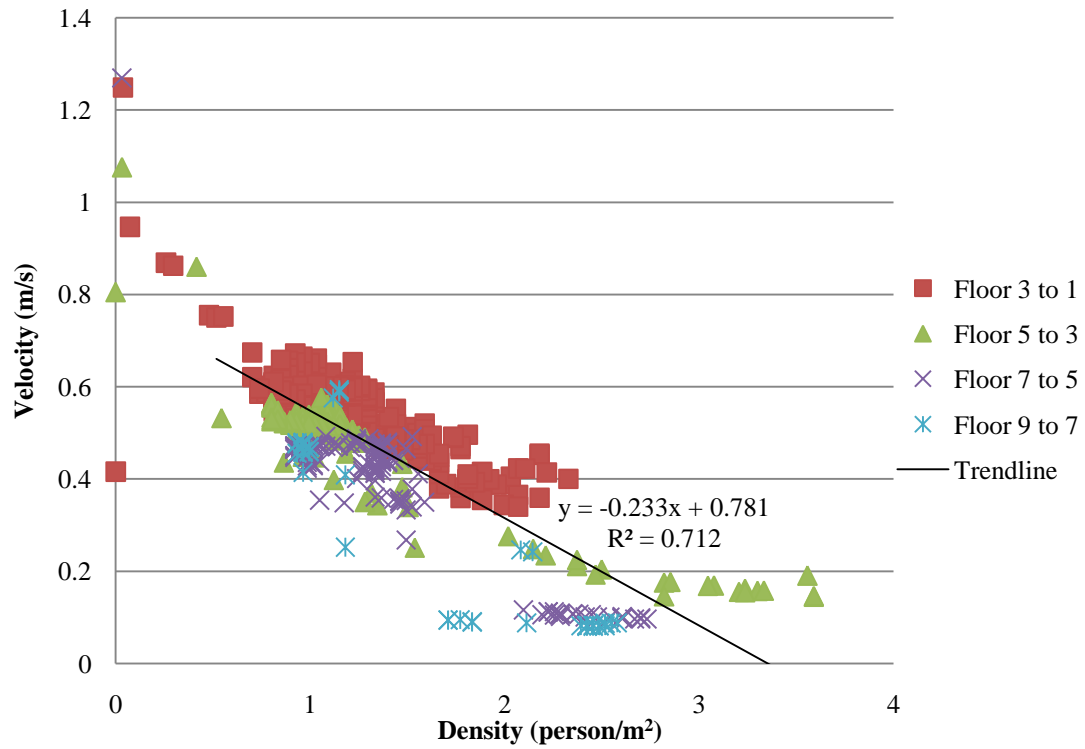


Appendix B: Graphs of Occupant Number, Local Speed, and Density

Stairwell 5A

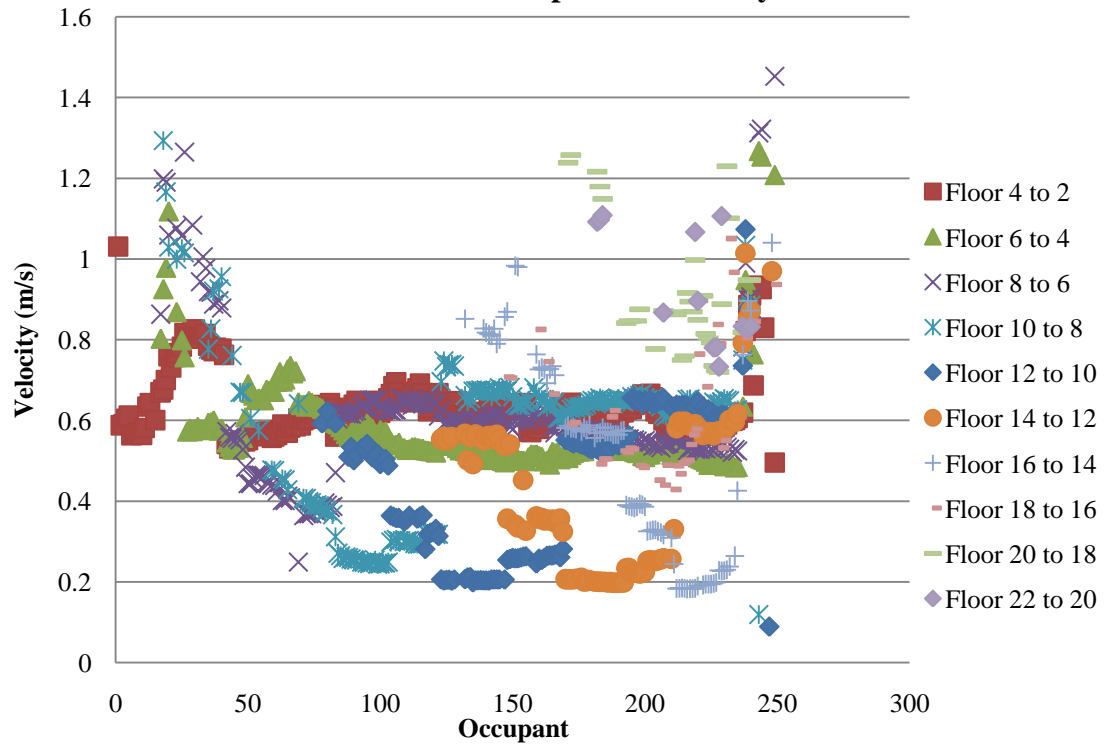


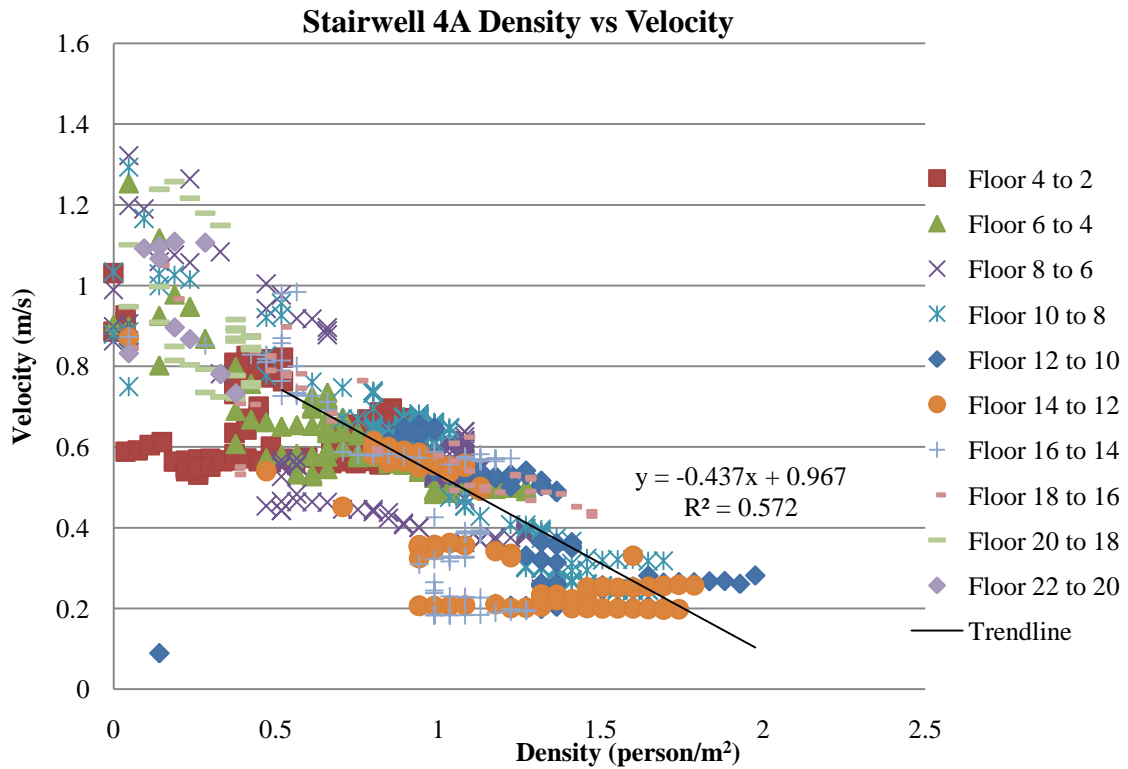
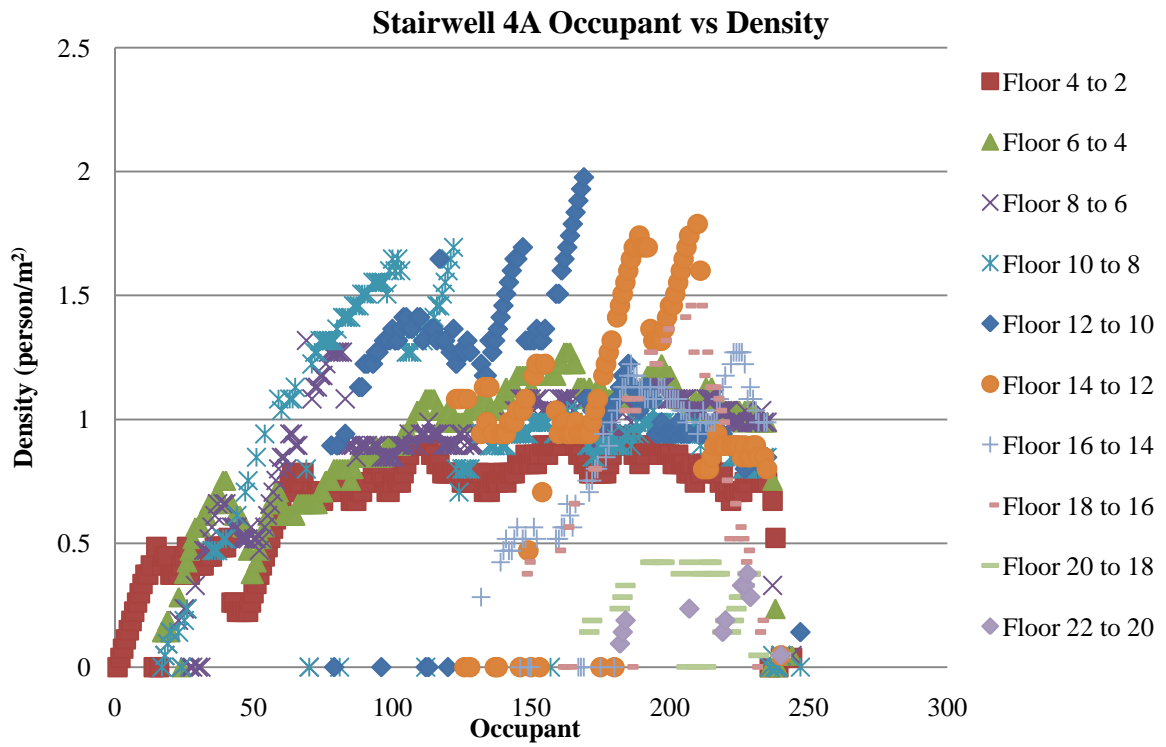
Stairwell 5A Density vs Velocity



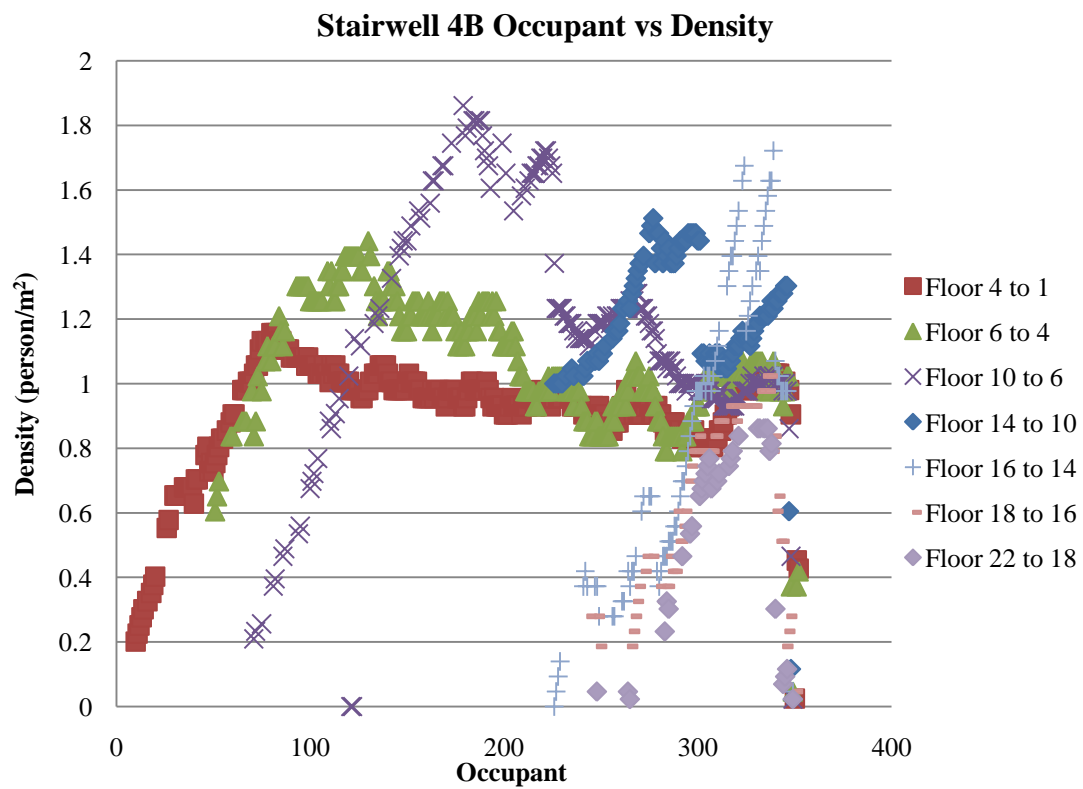
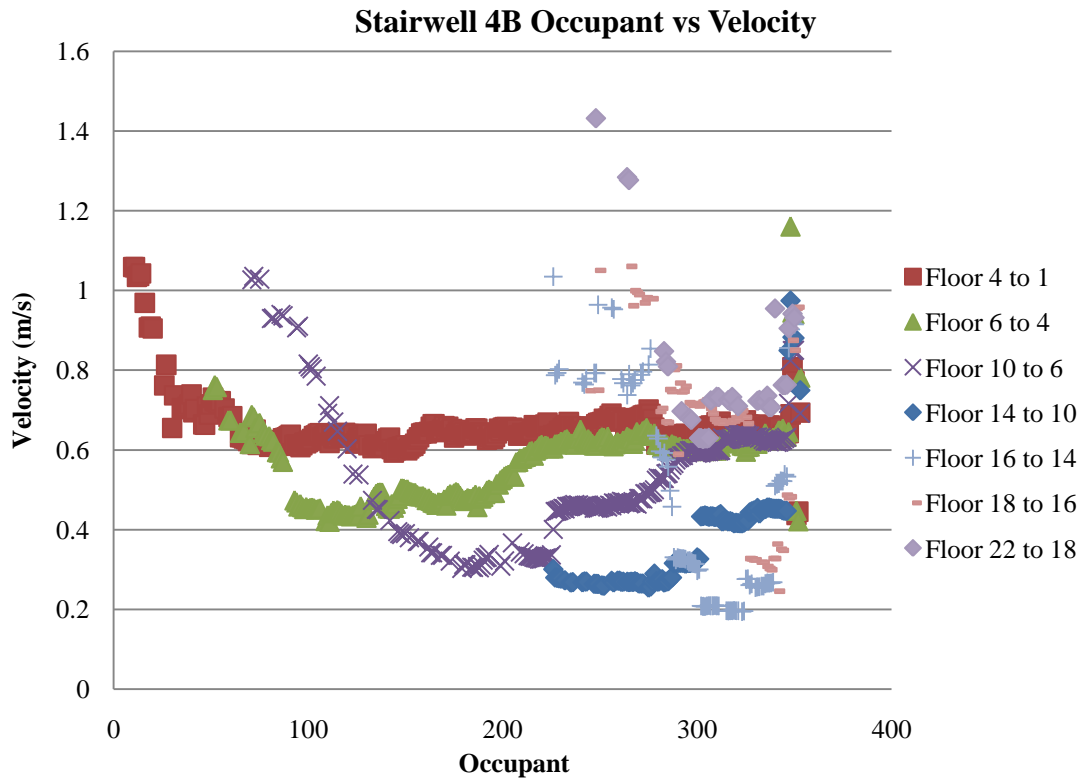
Stairwell 4A

Stairwell 4A Occupant vs Velocity

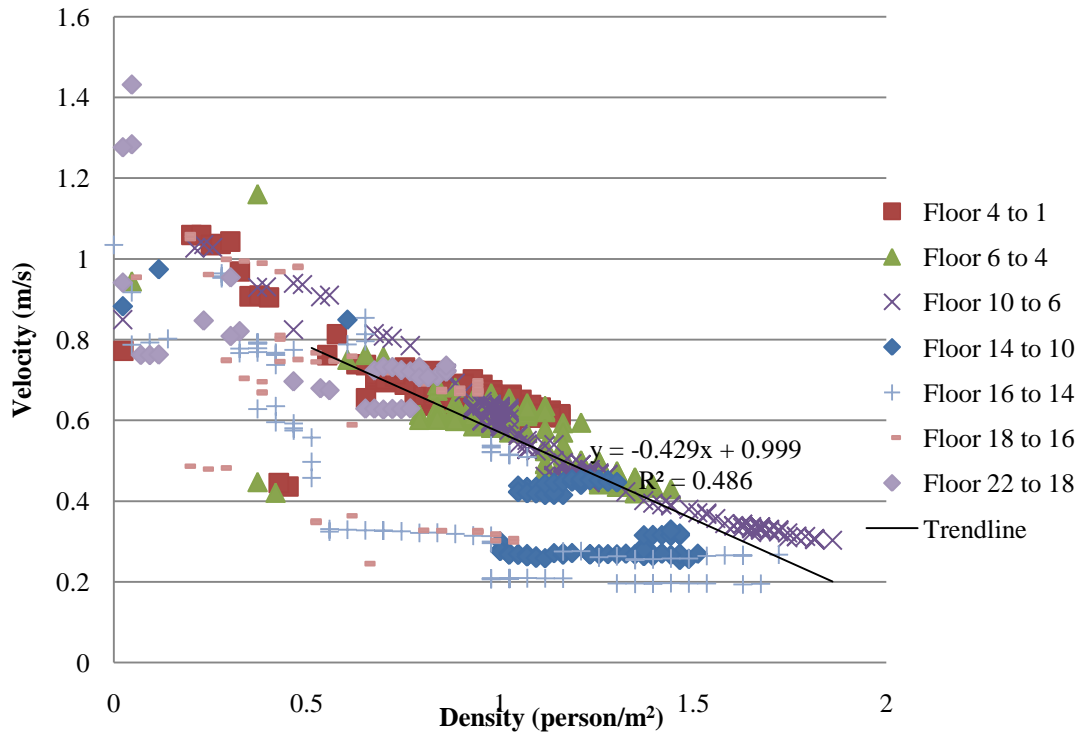




Stairwell 4B

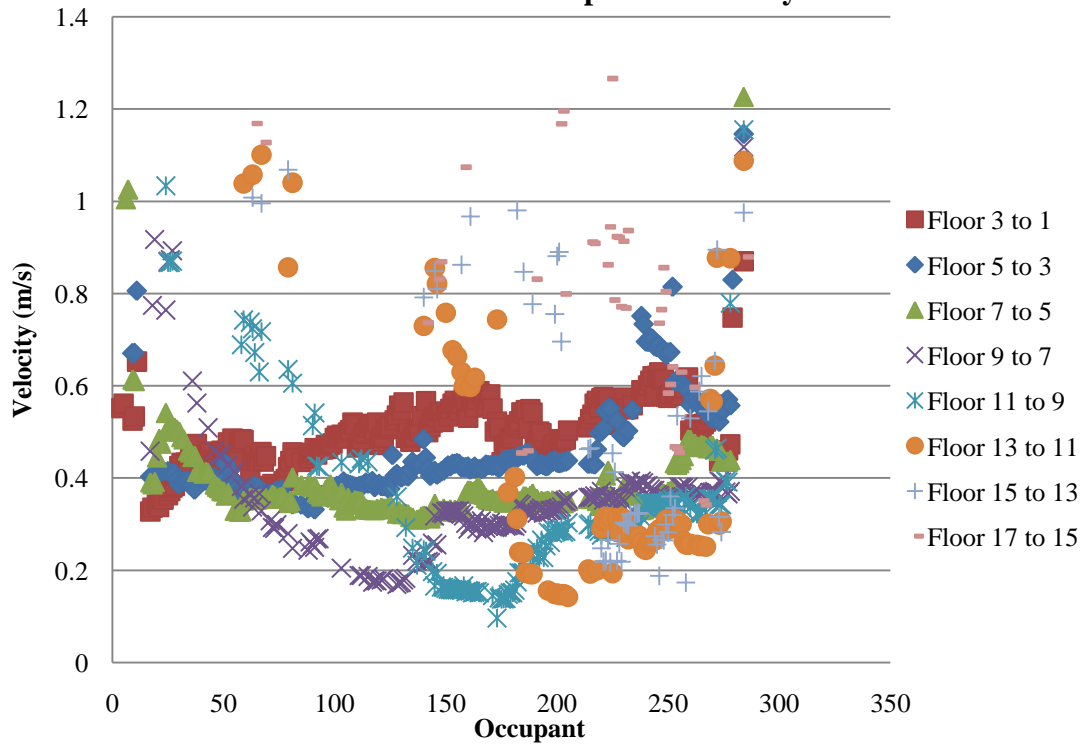


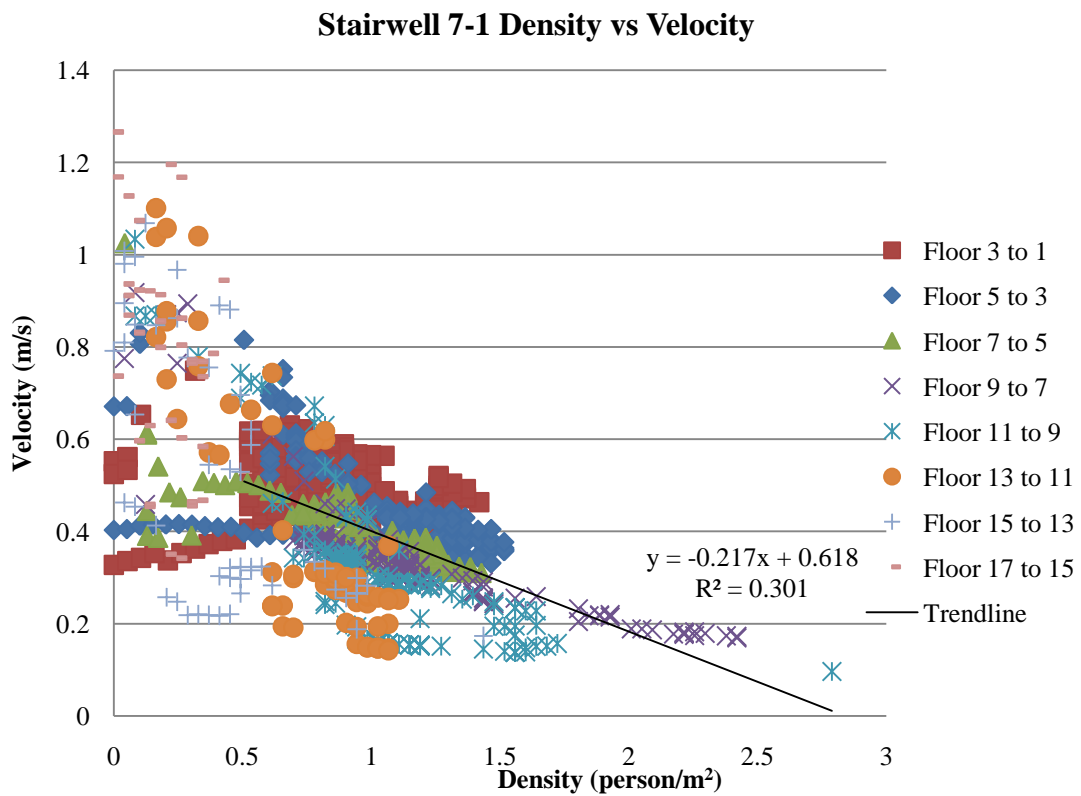
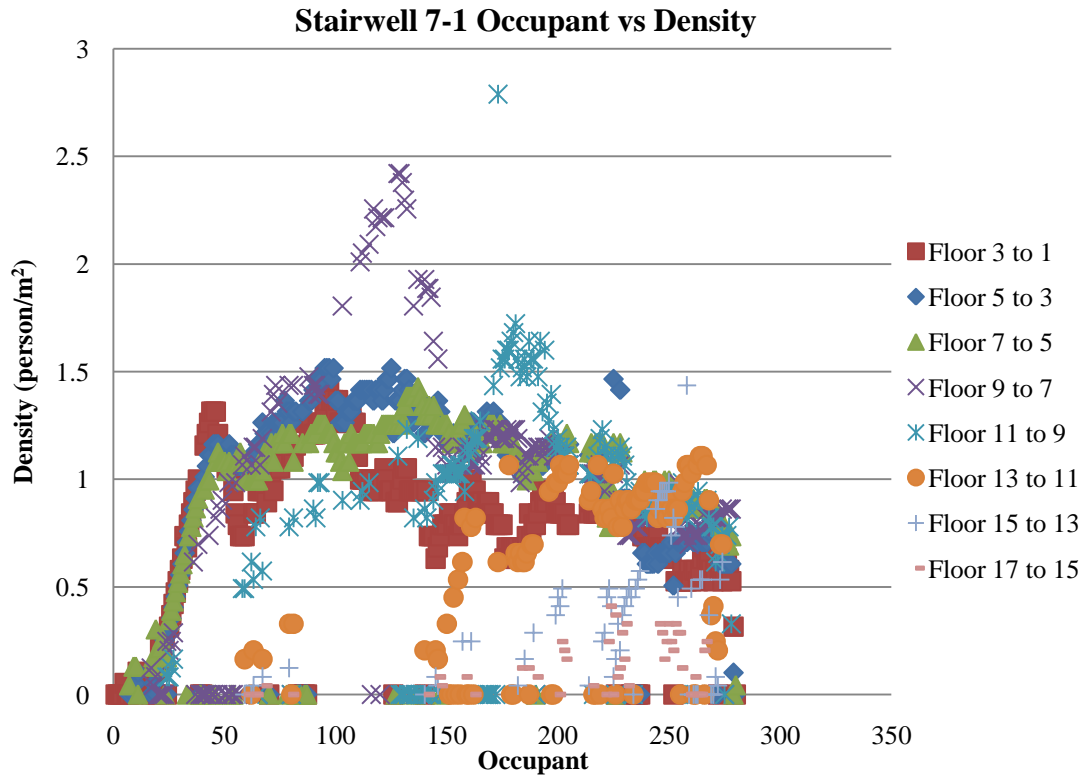
Stairwell 4B Density vs Velocity



Stairwell 7-1

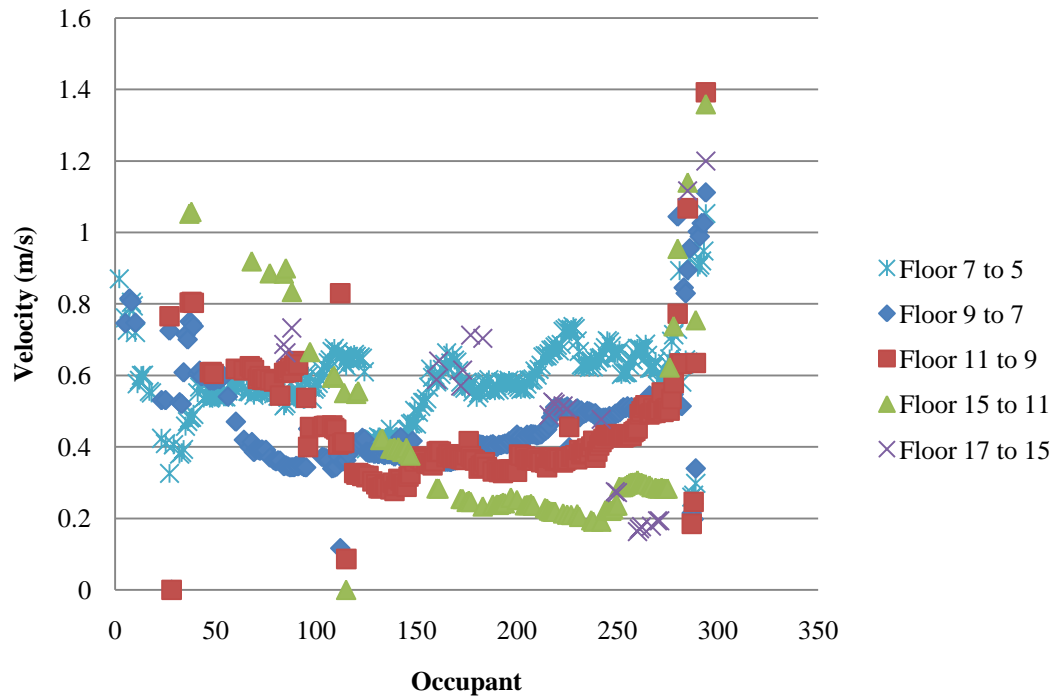
Stairwell 7-1 Occupant vs Velocity



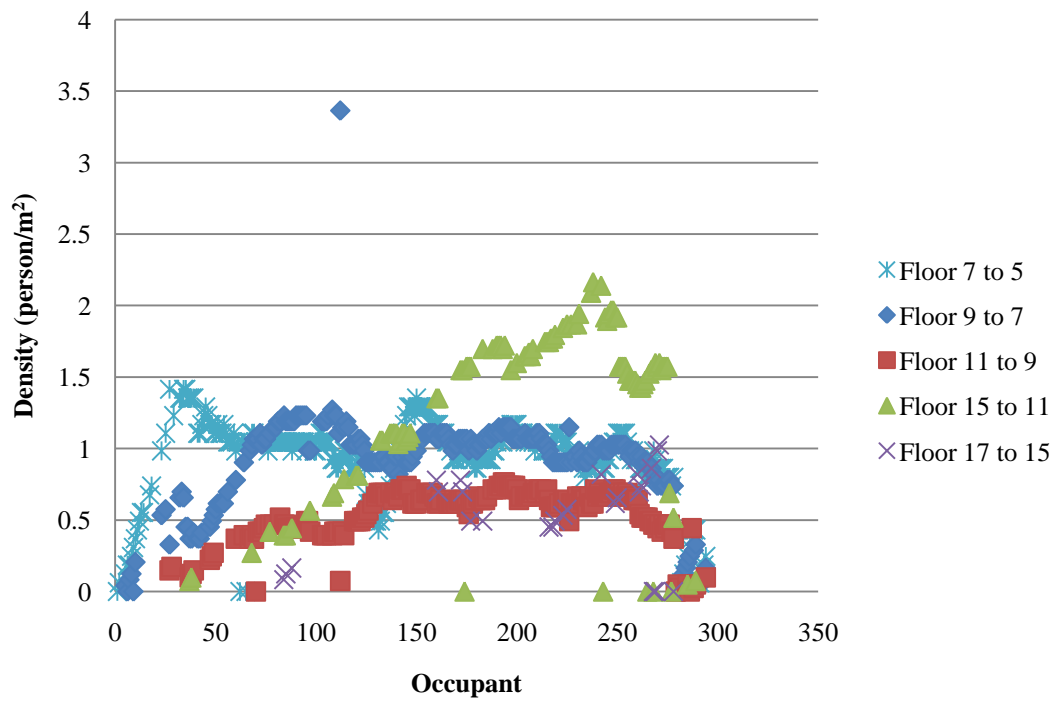


Stairwell 7-3

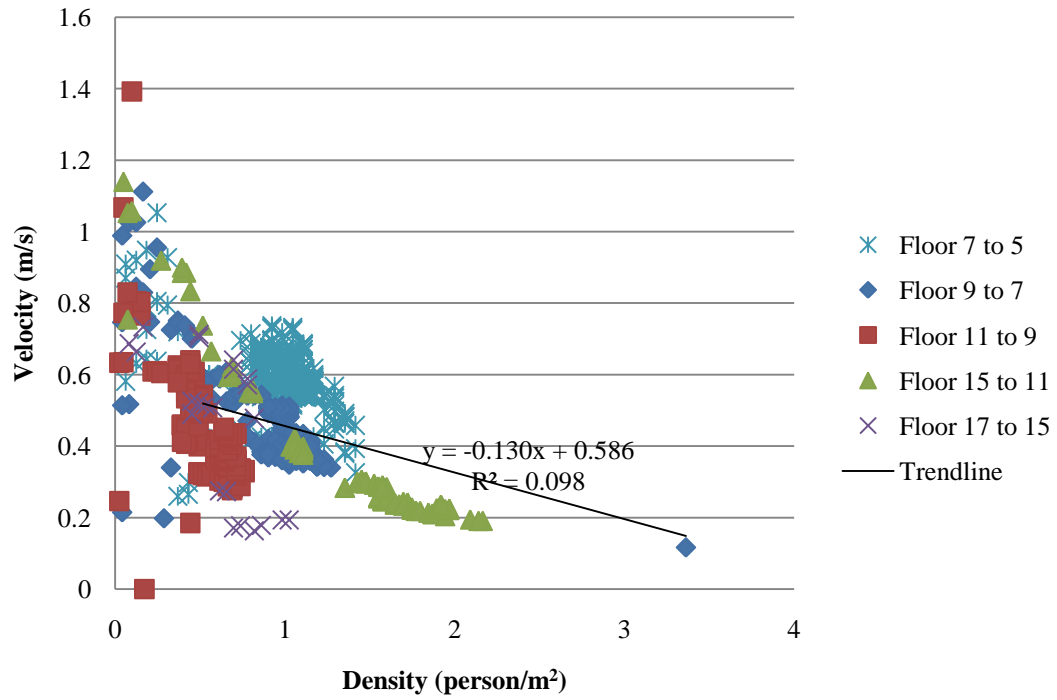
Stairwell 7-3 Occupant vs Velocity



Stairwell 7-3 Occupant vs Density

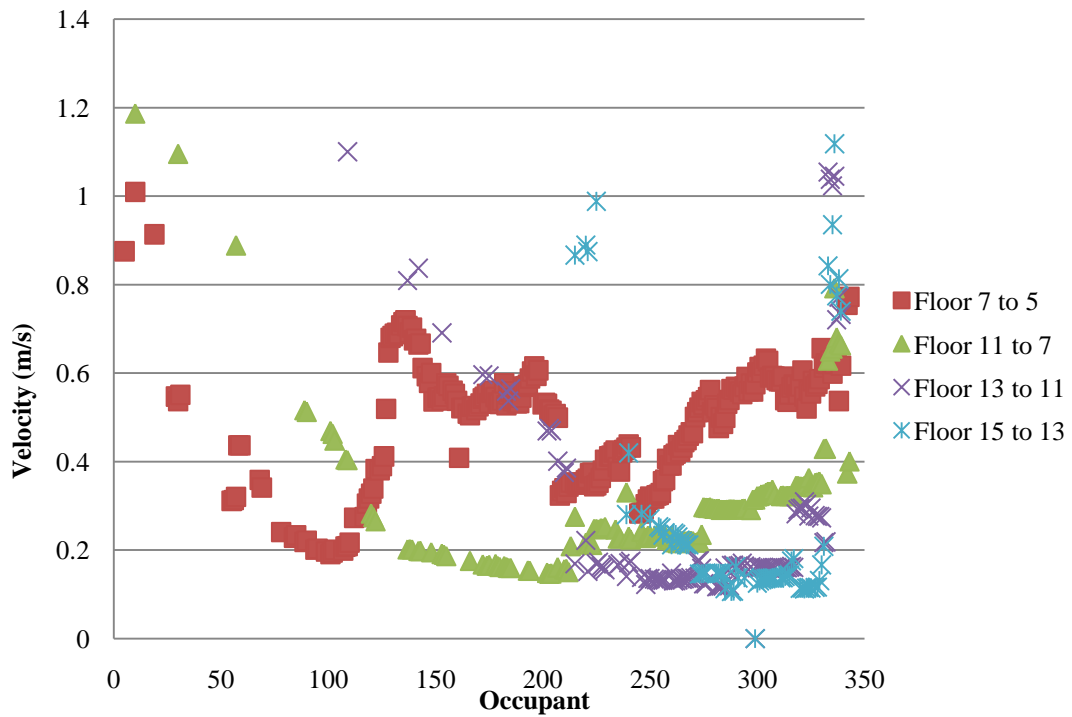


Stairwell 7-3 Density vs Velocity

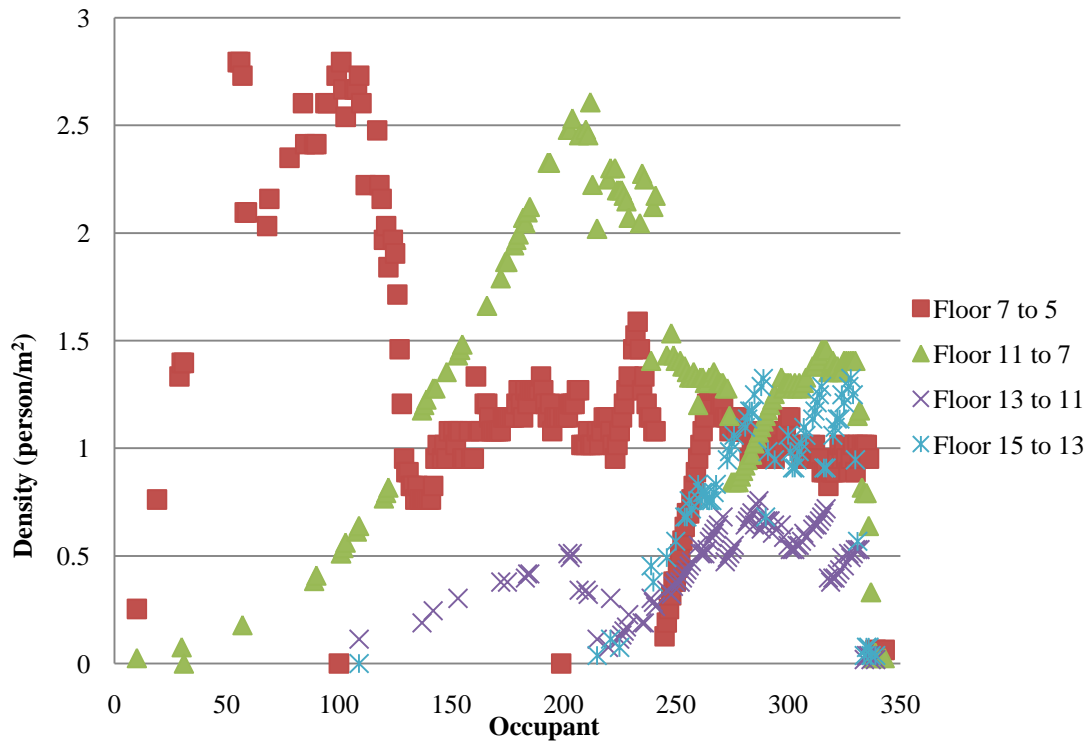


Stairwell 7-7

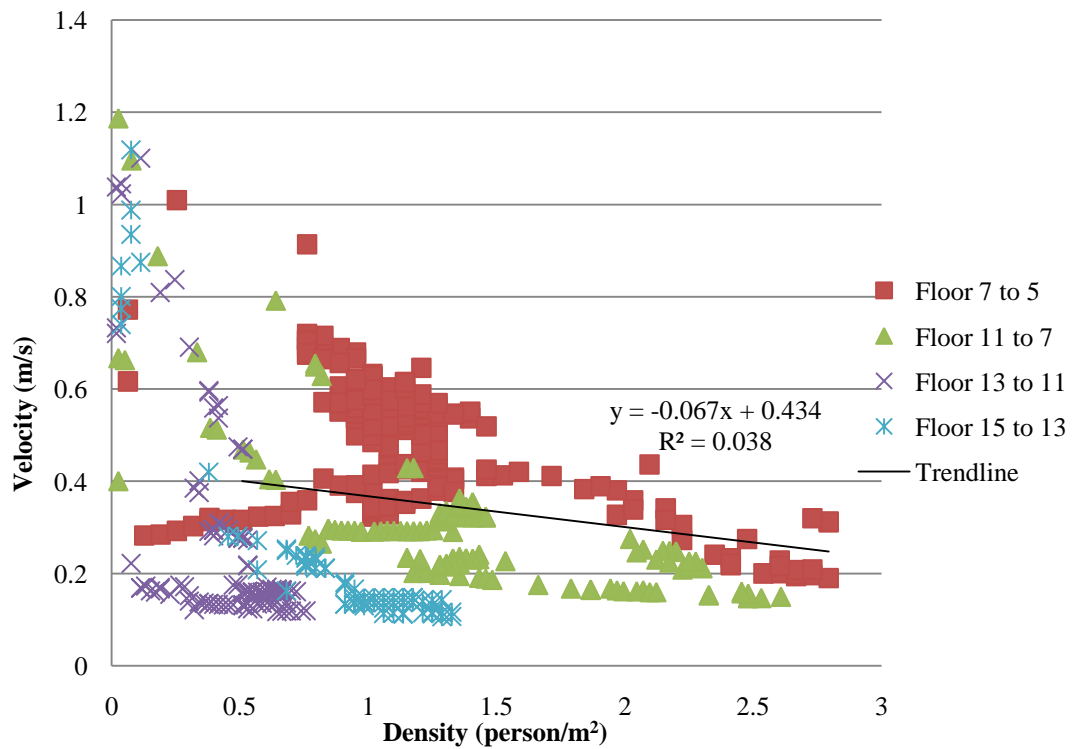
Stairwell 7-7 Occupant vs Velocity



Stairwell 7-7 Occupant vs Density

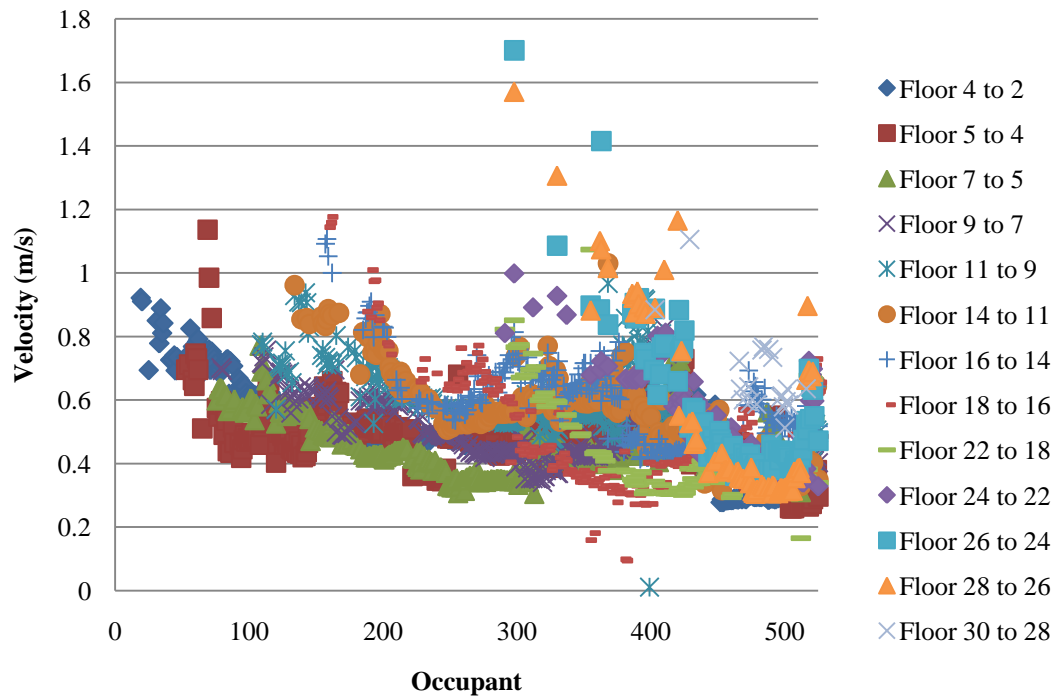


Stairwell 7-7 Density vs Velocity

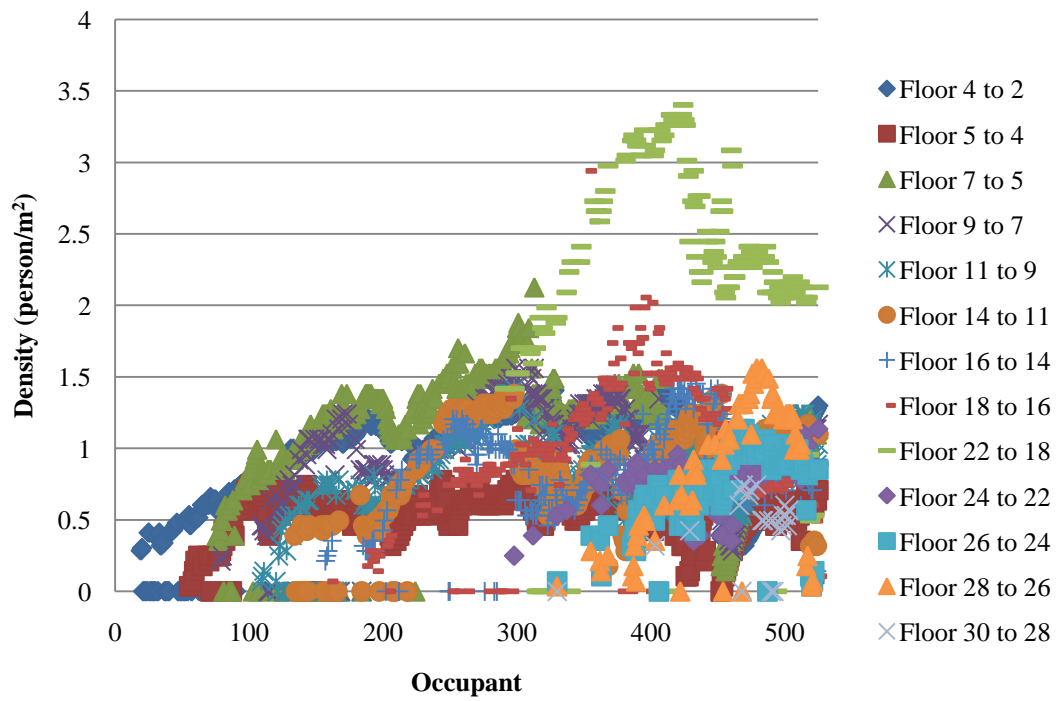


Stairwell 8

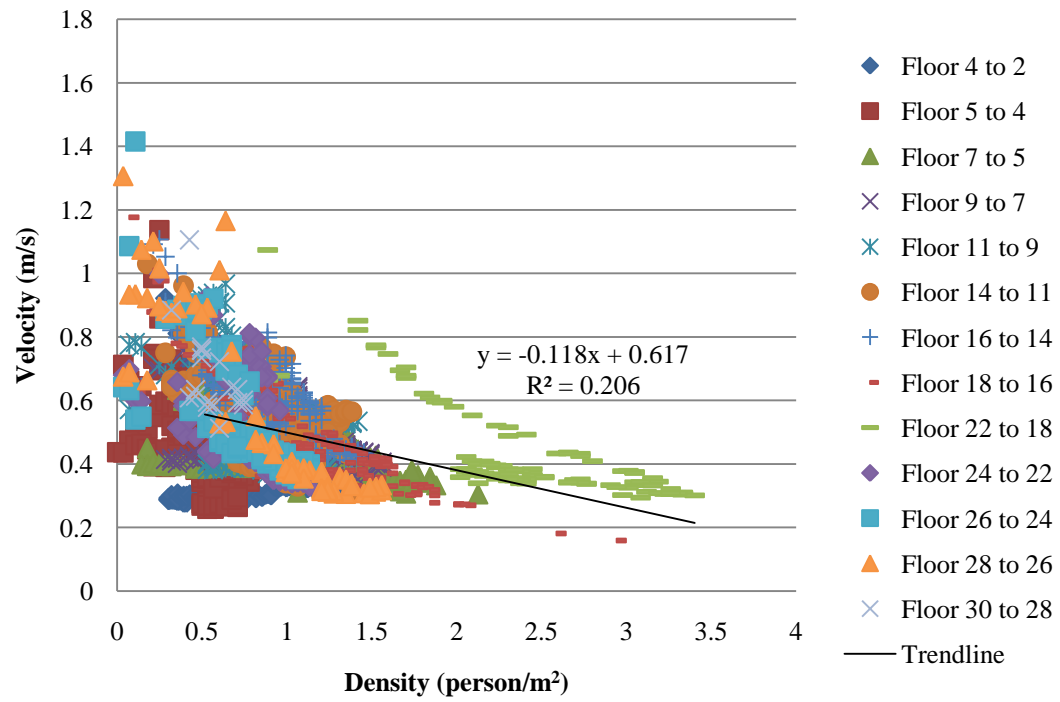
Stairwell 8 Occupant vs Velocity



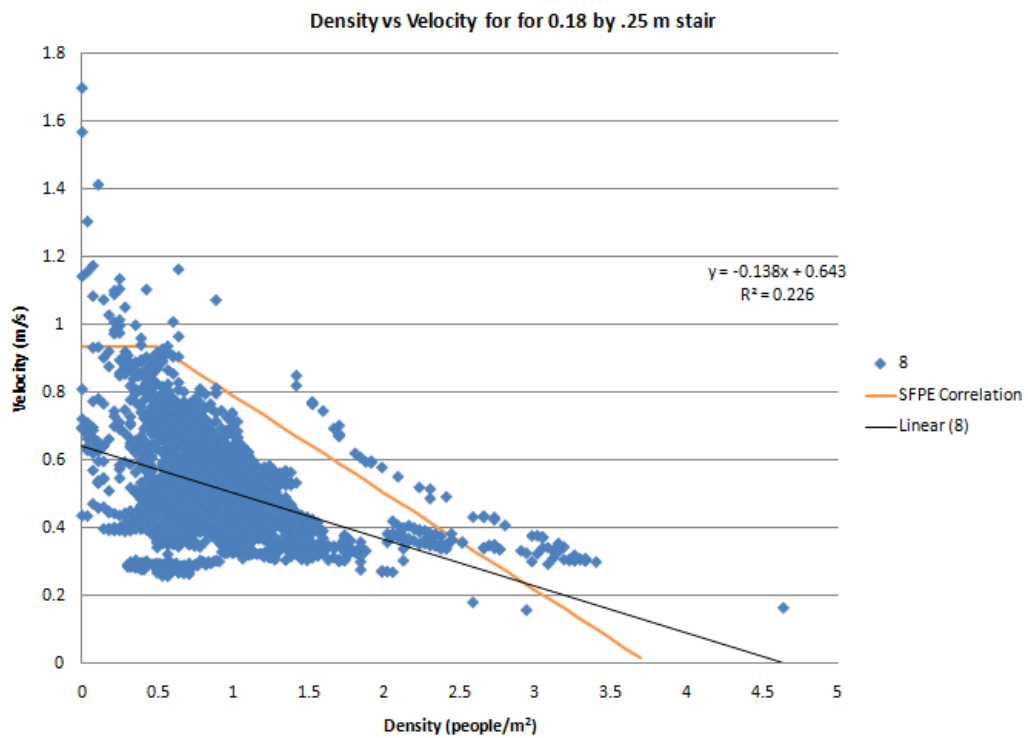
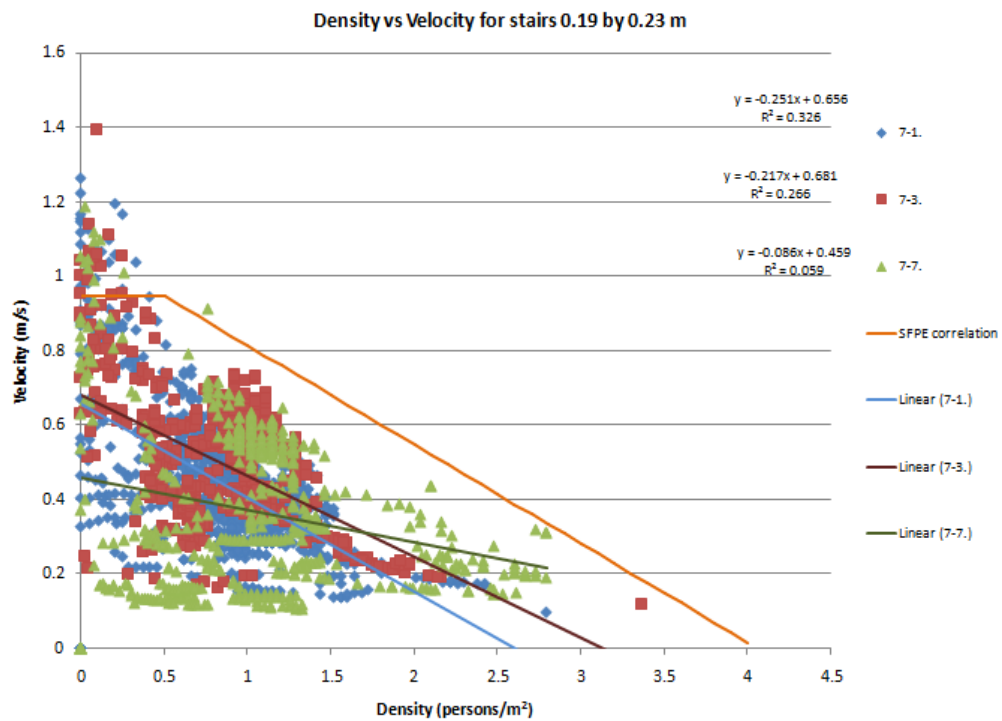
Stairwell 8 Occupant vs Density

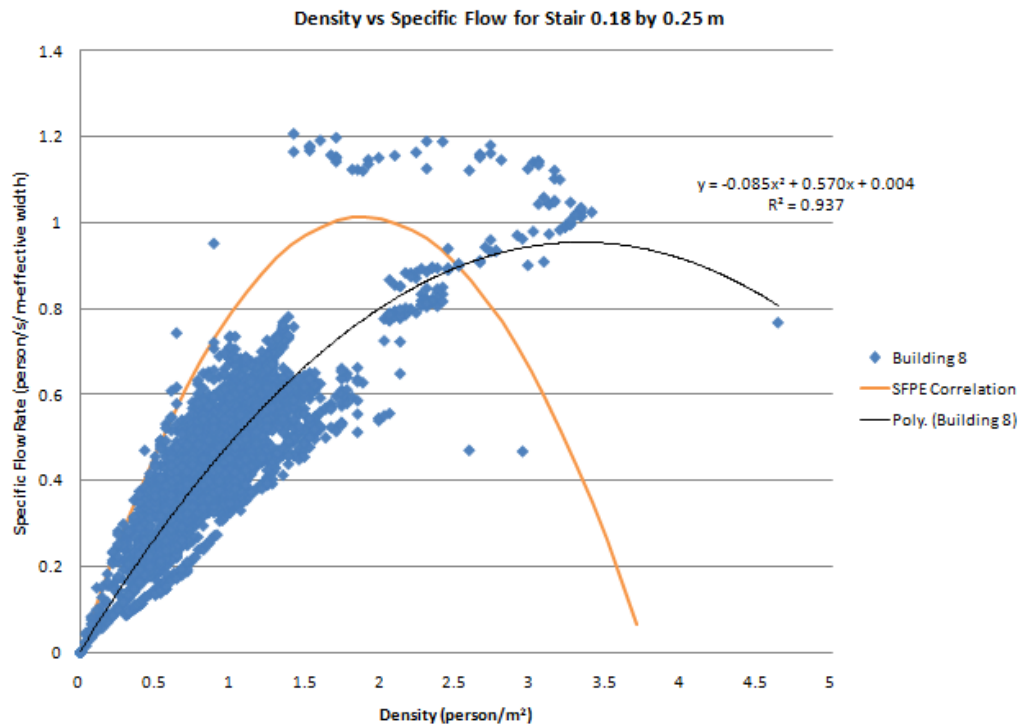
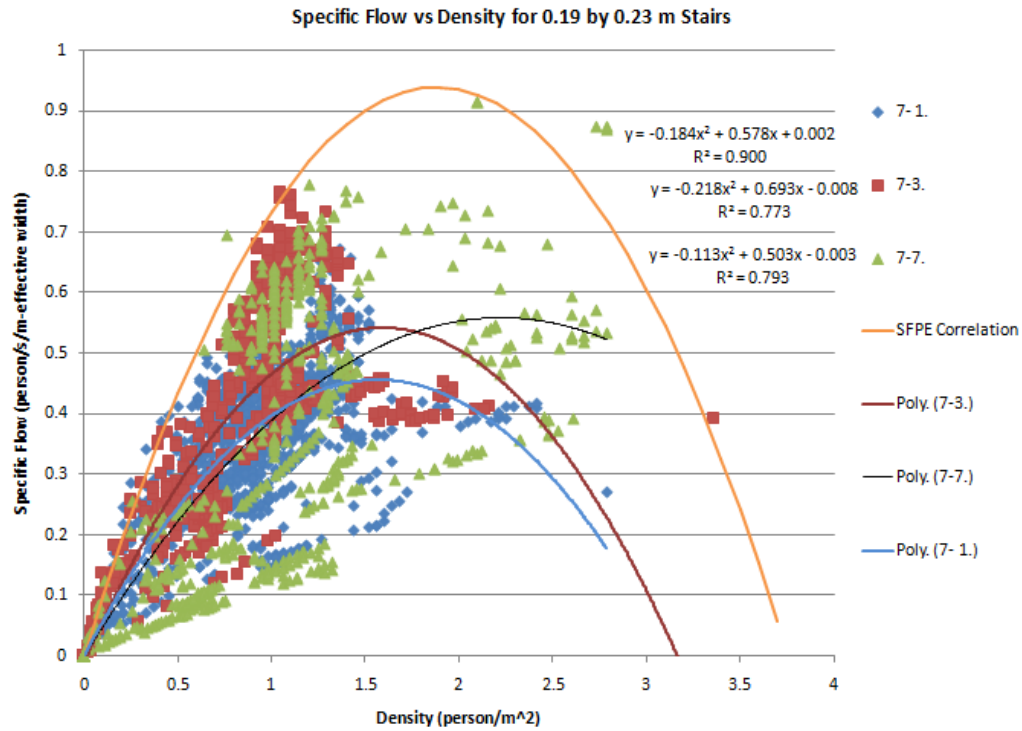


Stairwell 8 Density vs Velocity



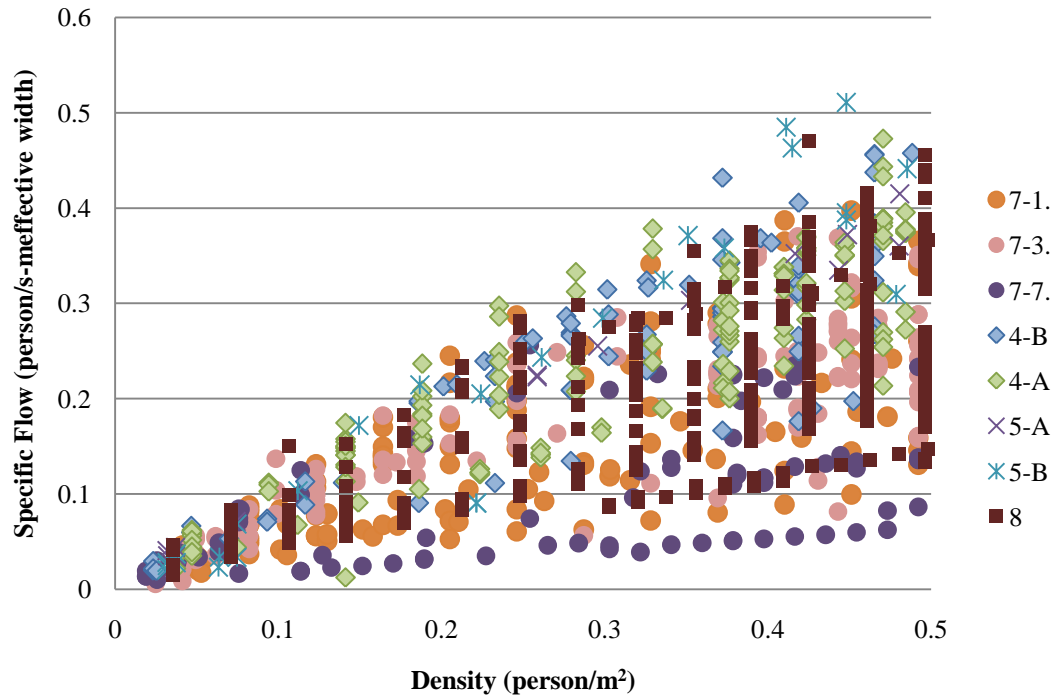
Appendix C: Graphs of SFPE Correlations with Raw Data



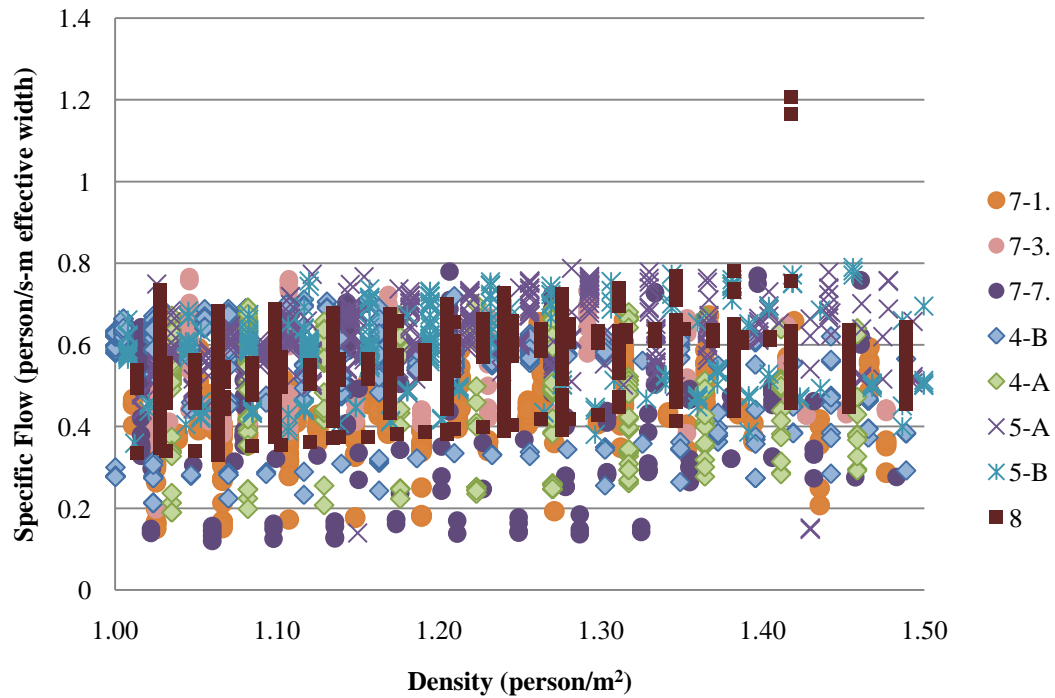


Appendix D: Density versus Specific Flow for All Stairwells Graphed by Density Ranges

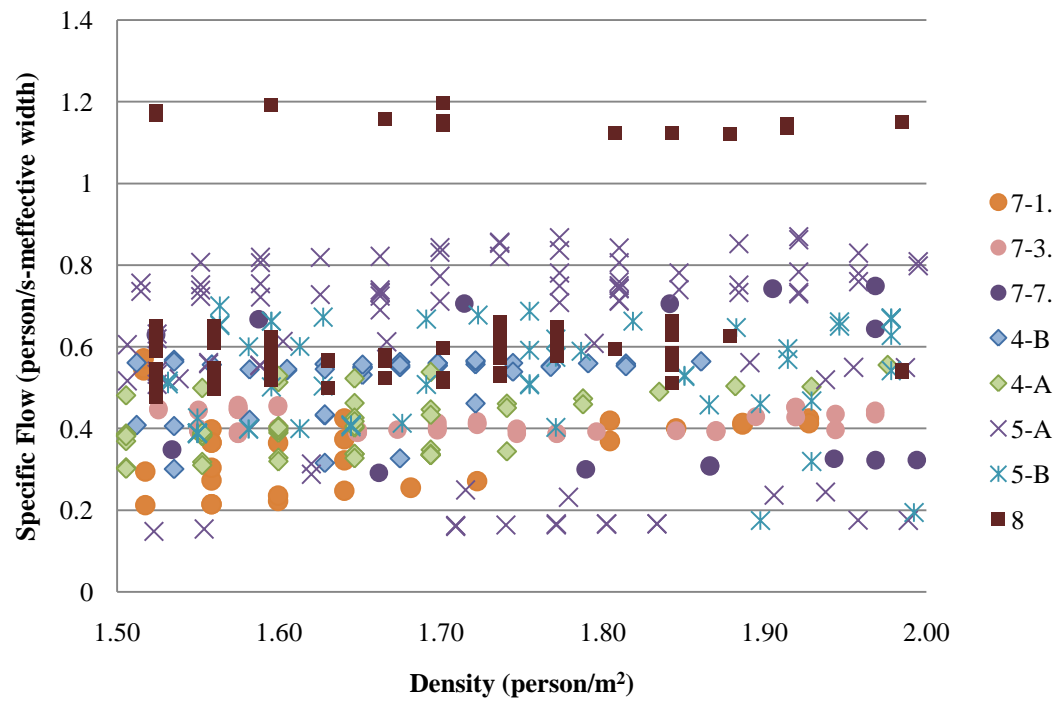
Density vs Specific Flow for 0.0-0.5 person/m²



Density vs Specific Flow for 1.0-1.5 person/m²



Density vs Specific Flow for 1.5-2.0 person/m²



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